**Faculdade de Engenharia da Universidade do Porto**

# Last-Mile Communications Systems for Smart Electric Distribution Grids

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*"Experience is what you get when you didn't get what you wanted."*

Randy Pausch in *Last Lecture - Achieving your Childhood Dreams*

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*David*

# Abstract

The recent paradigm change observed in the evolution of electric power systems has motivated a significant amount of research related with the smart grid concept. Different modes of operation, control algorithms and market integration strategies have focused on implementing increasingly dynamic electric power systems, targeting higher levels of efficiency, security and reliability while providing an economical advantage for the involved participants. Communications networks are the supporting infrastructure that should ensure the necessary information exchange among different entities according to the requirements introduced by the different applications envisaged for smart grids.

This thesis is focused on communications systems for the last-mile segment targeting electric distribution networks, where more changes are expected to occur within the SG concept. The work presented here involved in the first place the identification of the communication requirements that must be fulfilled to enable enhanced control strategies associated with microgrids concepts and related extensions.

A functional and logical architecture was defined to tackle the interconnection of hierarchical control structures and interactions with market structures. Two perspectives are considered towards the implementation of this type of architecture, considering the short and long term. Information flows and respective use-cases were defined to better understand the possible interactions between the involved entities.

A multi-microgrid control scheme was implemented to allow the evaluation of the system response when in the presence of uncertainties introduced in the set-point exchange mechanism. An emergency operation scenario was considered as the most demanding case, in which discriminated control sample periods are evaluated and the impact of communications uncertainties in the control scheme is carried out.

A characterization of the context upon which communications systems are expected to operate was performed using anonymized data provided by the Portuguese distribution system operator. This allowed a classification of different types of distribution networks and understanding the potential density of communicating nodes and the respective geographic scope.

A wireless multi-hop communication solution was evaluated in the context of the last-mile segment of smart grids for outdoors communications using geographic data to generate different scenarios with variable node positioning. According to the scenario under evaluation and the involved distance among potential communicating nodes, relays were used to ensure the necessary connectivity.

An exploratory work was conducted with the implementation of the IEEE 1901 physical layer transmission scheme defined in the standard, which despite targeting both indoors and outdoor scenarios is evaluated as a technological solution to ensure connectivity from the outdoor mesh network until the

premises of consumers, typically in an in-building environment. A turbo decoder was defined and implemented and an analysis of the different modulation schemes, code rates and compatible decoding algorithms of the standard was conducted.

A communications infrastructure for a microgrids laboratory was designed and implemented to allow its operation and serve as a test-bed of control solutions and communications technologies in a near-real environment. It was shown that its features allowed the evaluation of different operating scenarios through the remote configuration of the different devices of the electric infrastructure and emulation of uncertainties in the data exchange that can be associated with different communications technologies and solutions. The impact of these uncertainties was evaluated considering different operating scenarios.

# Resumo


A recente mudança de paradigma observada na evolução dos sistemas elétricos de potência tem motivado uma grande diversidade de atividades de investigação relacionadas com o conceito de rede inteligente. Diferentes modos de operação, algoritmos de controlo e estratégias de integração de mercado têm sido usados como forma de implementar sistemas elétricos de potência mais dinâmicos, que visam níveis de eficiência, segurança e fiabilidade mais elevados, assegurando contrapartidas económicas aos respetivos participantes. As redes de comunicações são a infraestrutura de suporte que deve assegurar a necessária troca de informação entre as diversas entidades, de acordo com os requisitos colocados pelas diferentes aplicações previstas para as redes inteligentes.

Esta tese está focada nos sistemas de comunicação para o segmento final das redes elétricas de distribuição, também conhecido por *last-mile* na designação anglo-saxónica, onde mais mudanças associadas ao conceito de rede inteligente são esperadas. O trabalho aqui apresentado envolveu em primeiro lugar a identificação de requisitos de comunicação para permitir estratégias de controlo avançadas associadas a conceitos de microrede e respetivas extensões.

Uma arquitetura funcional e lógica foi definida para lidar com a interligação de estruturas de controlo hierárquico com estruturas de mercado. Duas perspetivas são consideradas para a implementação deste tipo de arquitetura, considerando o curto e o longo prazo. Os fluxos de informação e os respetivos casos de uso foram definidos para melhor compreender as interações possíveis entre as entidades envolvidas.

Uma estrutura de controlo baseada em multi-microredes foi implementada de forma a permitir a avaliação da resposta de um sistema elétrico na presença de incertezas introduzidas no mecanismo de troca de informação de controlo. Um cenário de operação em emergência foi considerado como o caso mais exigente, no qual diferentes períodos de ações de controlo são avaliados bem como o impacto da incerteza dos sistemas de comunicações no mecanismo de controlo.

Uma caraterização do contexto no qual se espera que os sistemas de comunicações operem foi realizada utilizando dados fornecidos pelo operador de sistema Português, de forma anónima. Tal permitiu classificar diferentes tipos de redes de distribuição e avaliar a densidade de nós que poderão necessitar de comunicar bem como o respetivo âmbito geográfico.

Uma solução de comunicações sem fios multi-salto (*multi-hop*) foi avaliada no contexto da *last-mile* das redes inteligentes, para comunicações em ambiente exterior utilizando dados geográficos para a geração de diferentes cenários com variabilidade no posicionamento dos nós. De acordo com o tipo de cenário a ser avaliado e as distâncias entre os nós que potencialmente têm que comunicar, nós repetidores foram adicionados para garantir a conetividade necessária.

A implementação ao nível físico do mecanismo de transmissão definido na norma IEEE 1901, que apesar de ter como alvo tanto cenários interiores como exteriores, foi avaliada como uma solução que permite assegurar a conetividade entre uma rede rede emalhada multi-salto (*multi-hop mesh network*) e a instalação dos utilizadores, num ambiente de interior de edifício, e é apresentado como trabalho exploratório. Um descodificador turbo foi definido, implementado e avaliado tendo em conta os diferentes esquemas de modulação, taxas de codificação e algoritmos de descodificação compatíveis com a norma.

Uma infraestrutura de comunicações para um laboratório de microredes foi projetada e implementada de forma a permitir a sua operação e a servir como plataforma de testes de soluções de controlo e de tecnologias de comunicações num ambiente próximo do real. Mostrou-se que as suas caraterísticas permitem a avaliação de diferentes cenários de operação através da configuração remota dos diferentes dispositivos da infraestrutura elétrica, bem como da emulação de incertezas na troca de informação que podem ser associadas a diferentes soluções e tecnologias de comunicações. O impacto destas incertezas foi avaliado considerando diferentes cenários de operação.

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# Acronyms and Abbreviations

| | |
|---|---|
| AGC | Automatic Generation Control |
| AMI | Advanced Metering Infrastructure |
| AMM | Automated Meter Management |
| AMR | Automatic Meter Reading |
| AODV | Ad hoc On-Demand Distance Vector Routing |
| AP | Access Point |
| AWGN | Additive White Gaussian Noise |
| BAN | Business Area Network |
| BPL | Broadband over PowerLine |
| CA | Contingency Analysis |
| CAMC | Central Autonomous Management Controller |
| CDF | Cumulative Distribution Functions |
| CERTS | Consortium for Electric Reliability Technology Solutions |
| CHP | Combined Heat and Power |
| CSMA | Carrier Sense Multiple Access |
| CSMA/CA | CSMA with Collision Avoidance |
| DA | Distribution Automation |
| DAS | Data Acquisition Server |
| DBPSK | Differential Binary Phase Shift Keying |
| DER | Distributed Energy Resources |
| DFIM | Doubly-Fed Induction Machine |
| DG | Distributed Generation |
| DM&CS | Distribution Management and Control System |
| DMS | Distribution Management System |
| DoE | Department of Energy |
| DQPSK | Differential Quadrature Phase Shift Keying |
| DR | Demand Response |
| DSO | Distribution System Operator |
| DSSS | Direct Sequence Spread Spectrum |
| DTC | Distribution Transformer Controller |
| EAN | Extended Area Network |
| EB | Energy Box |
| EB-EVMV | Energy Box for Electric Vehicles at Medium Voltage |
| EDSO | European Distribution System Operators |
| EPRI | Electric Power Research Institute |

| | |
|---|---|
| EREV | Electric Range Extender Vehicle |
| ESO | European Standards Organization |
| EV | Electric Vehicle |
| FACTS | Flexible AC Transmission System |
| FAN | Field Area Network |
| FDD | Frequency Division Duplex |
| FDIR | Fault Detection, Isolation and Service Restoration |
| FEC | Forward Error Correction |
| FEV | Full Electric Vehicle |
| FSK | Frequency Shift Keying |
| GHG | Green House Gas |
| GoF | Goodness of Fit |
| GW | Gateway |
| GWAC | Grid Wise Architecture Council |
| HAN | Home Area Network |
| HV | High Voltage |
| IAN | Industrial Area Network |
| IAP | Interoperability Architectural Perspectives |
| ICE | Internal Combustion Engine |
| ICT | Information and Communications Technologies |
| IEC | International Electrotechnical Commission |
| IED | Intelligent Equipment Devices |
| IEEE | Institute of Electrical and Electronics Engineers |
| IP | Internet Protocol |
| ISM | Industrial Scientific and Medical |
| ITU | International Telecommunication Union |
| ITU-T | ITU Telecommunications Sector |
| IVVC | Integrated Voltage/VAR Control |
| LC | Load Controller |
| LE | Load Estimation |
| LLR | Log-Likelihood Ratio |
| LM | Load Modeling |
| LOADng | Lightweight On-demand Ad hoc Distance-vector Routing Protocol - Next Generation |
| LoS | Line-of-Sight |
| LV | Low Voltage |
| M-C | Monte Carlo |
| M*a*P | Maximum *a posteriori* Probability |
| MAP | Mesh Access Point |
| MBC | Medium Behavior Controller |
| MC | Microsource Controller |
| MG | Microgrid |
| MGAU | Microgrid Aggregation Unit |
| MGCC | Microgrid Central Controller |
| MIMO | Multiple Input Multiple Output |
| MMG | Multi-Microgrid |

| | |
|---|---|
| MV | Medium Voltage |
| NAN | Neighborhood Area Network |
| NB-PLC | Narrow Band PLC |
| NIST | National Institute for Standards and Technology |
| O-QPSK | Offset Quadrature Phase Shift Keying |
| OFDM | Orthogonal Frequency Division Multiplexing |
| OFDMA | Orthogonal Frequency Division Multiple Access |
| OLTC | On-Load Tap-Changer |
| ONR | Optimal Network Reconfiguration |
| PAP | Priority Action Plan |
| PB | PHY Block |
| PDF | Probability Density Function |
| PLC | Power Line Communications |
| PMU | Phasor Measurement Units |
| PRIME | PoweRline Intelligent Metering Evolution |
| PSK | Phase Shift Keying |
| PV | Photovoltaics |
| QAM | Quadrature Amplitude Modulation |
| QoS | Quality of Service |
| RAU | Regional Aggregation Unit |
| RES | Renewable Energy Sources |
| RFI | Request for Information |
| RPC | Relay Protection Coordination |
| RPL | Routing Protocol for Low Power and Lossy Networks |
| RTT | Round-Trip Time |
| RTU | Remote Terminal Unit |
| SCA | Short Circuit Analysis |
| SCADA | Supervisory Control and Data Acquisition |
| SDO | Standard Development Organization |
| SER | Symbol Error Ratio |
| SG | Smart Grids |
| SGAM | Smart Grid Architecture Model |
| SGIP | Smart Grid Interoperability Panel |
| SGIRM | Smart Grid Interoperability Reference Model |
| SM | Smart Meter |
| SNR | Signal to Noise Ratio |
| SSC | Smart Substation Controller |
| STA | End Station |
| SUN | Smart metering Utility Network |
| SVC | Static Var Compensators |
| TDD | Time Division Duplex |
| TSO | Transmission System Operator |
| TVWS | TV White Space |
| V2G | Vehicle-to-Grid |
| V2H | Vehicle-to-Home |

| | |
|---|---|
| VSI | Voltage Source Inverter |
| WACS | Wide Area Control Systems |
| WAMS | Wide Area Monitoring Systems |
| WAN | Wide Area Network |
| WAPS | Wide Area Protection Systems |
| WASA | Wide Area Situational Awareness |
| Wi-Fi | Wireless Fidelity |
| WiMAX | Worldwide interoperability for Microwave Access |
| WLAN | Wireless Local Area Network |
| WMN | Wireless Mesh Network |
| WPAN | Wireless Personal Area Networks |

# Chapter 1

# Introduction

The electric power grid is a set of interconnected systems that allow electric energy to flow from generation facilities to consumers. The first implementations of electric grids, back in the 19th century, were performed with the power production near the consumption needs. This was the case of factories and large houses where own generators were used to feed devices that required electricity to operate. Street lighting and railways were among the first applications requiring intense use of electric energy, which along with the economy of scale vision introduced early in the 20th century, by the industrial era, led to the centralization of electric power generation.

Following the unbundling of the electric energy business in the 90s, the power system has suffered a segmentation leading to the appearance of utilities as electric power companies operating in segments such as generation, transmission and distribution. The interconnection of electrical grids allowed electric systems to become more robust, reliable and flexible but it also required coordination and information exchange. Technology has been an important factor in enabling a large-scale operation with enhanced monitoring and automation schemes along with market integration leading to more robust power systems.

Given the nature of the transmission segment and its role in interconnecting a diversity of systems, communications have played an important role in aspects such as operation, market transactions, security and the integration of generation and distribution systems. Nevertheless, this segment has been relying on local and automatic discrete control functions to overcome disturbances while ensuring reliable and robust operation. The evolution of the distribution segment has been up until recently somewhat occasional, although technological advances have been introduced. On the distribution side the electric network was mainly passive, operating in a feeding load scheme, with limited interaction between the supply and the loads, which required little or no communications at all [1]. Traditionally the electric distribution networks had limited or reduced metering and monitoring mechanisms and restricted control schemes, used only in particular cases like large consumers.

In contrast with the past, electric grids have changed significantly in the last decade. Besides the unavoidable evolution in terms of technology, with impact in energy efficiency, there are also environmental, social and economic aspects driving the integration of Renewable Energy Sources (RES) in Europe. According to the Eurostat energy indicators [2], presented in Fig. 1.1, the generation segment in Europe has been incorporating a significant increase in the amount of RES whilst reducing the dependence on

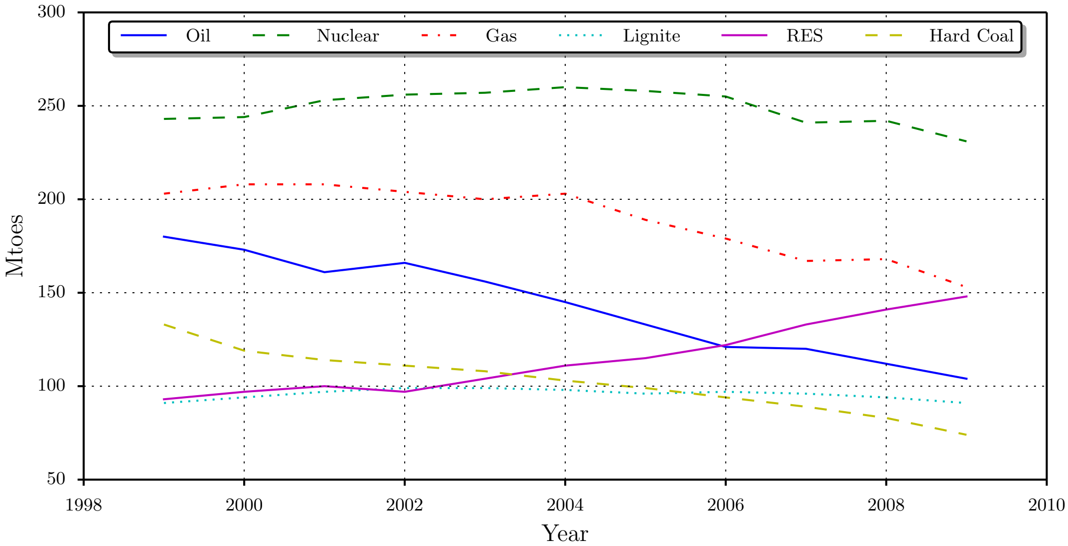



Figure 1.1: Primary Energy Production by Fuel[1]

non-renewable primary energy production. An interesting fact in the evolution of the power generation, pointed out in [3], is that through time the electricity production started by being decentralized, then it became centralized and currently is incorporating again decentralized generation. With the distribution segment integrating Distributed Generation (DG), the energy production became more decentralized and along with it new challenges appeared, with some of them being addressed in different research activities.

The appearance of active distribution cells, like microgrids, and consequently their extension and association in multi-microgrids, has been demonstrating the increased importance of the distribution segment within the power system. This has motivated the development of different control strategies to take advantage of distributed and controllable resources. This has highlighted the importance of communications networks as a supporting infrastructure that is capable of ensuring the necessary information exchange in a secure, efficient and reliable way to allow the different modes of operation of the electric distribution network.

## 1.1 Motivation

Given the paradigm change in electric power grids, introduced by concepts such as Smart Grids (SG), several applications supported by enhanced operation and control schemes are expected to be implemented. This will require a communications infrastructure capable of conveying a wide variety of information flows while supporting different requirements, which will be set according to each application to support. This means that different communications networks will be defined, ensuring the necessary diversity in

[1] Adapted from Eurostat data

terms of functionality and performance. As such, an effort will have to be made in ensuring the necessary interworking across the SG, which means that interoperability among potentially heterogeneous communications network is vital.

The changes introduced by the evolution of electric grids are set to have a significant impact in the whole power system. However, the distribution grid is the segment where most significant changes are expected to take place. The penetration of Distributed Energy Resources (DER) in the distribution grid will bring new challenges and difficulties that will require refined control architectures to ensure a proper system operation, from the technical and market point of view. These architectures will have to support the exchange of information between legacy and new systems, in a segment that was not originally designed to have applications that required significant amounts of data exchange.

The applications foreseen for SGs, particularly for the electric distribution network, have made clear the importance of a communications infrastructure that is able to cope with the imposed requirements. Although communications have been overlooked in this segment, mainly because they were rarely needed, there has been in the last decade a particular interest in promoting its use in order to accommodate new applications.

Smart metering is one of the most significant examples of the new applications introduced within SGs, where remote schemes have been explored by utilities to allow the collection of information of electric meters installed in different customers, in a passive fashion. In terms of communications infrastructure this is an application that will potentially span over several communications networks, interconnecting customers with centralized systems of the electric grid. Despite all different concepts and implementations, the objective was to have this information available for billing purposes and rudimentary fraud control, reducing the man-labor required in manual meter reading. This idea was also welcomed by other utilities, such as water or heat suppliers, who saw in this application a way to reduce cost and have a more detailed metering collection scheme. However, a more dynamic and active approach has be sought by utilities in using smart metering to promote an enhanced interaction with the end customer.

The collection of data from meters imposes very low requirements in terms of communications, since the periodicity of the information retrieval is high. However, there are other applications intended to improve the operation of SGs in terms of efficiency, reliability and security whilst introducing economic and environmental benefits, which will pose more stringent requirements. These will require the integration of active elements, which in turn will involve different operation and control schemes. From the technical perspective different scenarios will have to be considered where communications infrastructures can have a significant impact, by allowing enhanced monitoring and control strategies in a segment, like the distribution, where they are not common. Such strategies will take advantage of the expected increase in sensing capability of the electric grid, and from the emergence of controllable entities that can actively participate in the system operation. Therefore, decentralized and flexible architectures, highly dependent on communications networks, are being explored as an alternative to historical centralized approaches for managing the system operation. This means that information exchange requirements that can vary from real-time to best-effort applications will have to be supported.

Besides the technical operation, the advent of SG is regarded by the electric power system stakeholders as an opportunity to introduce enhanced market participation. It will allow more services to be offered to all participants, such as demand side management, demand side response, smart metering, retail price oriented and advanced ancillary services. It becomes feasible the exchange of services between different participants in the electric power market. Historically speaking, electric energy customers were mainly consumers of electricity; however, this paradigm has recently changed with the integration of RES in the form of microgeneration like photovoltaics (PV), small wind turbines and micro combined heat-power units, allowing customers to produce electric energy and inject it into the grid. This new role of end-users as "prosumers" will also allow them, from a market perspective, to have a more active participation on system operation. The communications requirements associated with market operation are less stringent. It involves the day-ahead operation, where negotiations for operations in the present day are made the day before, and the intra-day operation where negotiation procedures are expected to take place within time periods as low as 15 minutes. This means that market operation is not set to need "real-time" communications requirements.

The importance of DERs in electric grids has been demonstrated in concepts such as microgrids both in interconnected and islanded modes. The control and coordination of microgrid elements, such as storage devices and controllable loads, is supported by a communications infrastructure that allows the deployment of advanced management schemes, especially important when conducting emergency control procedures [4]. One particular emergent DER element that will impact the operation of the electric grid is the Electric Vehicle (EV). The particular characteristics of EVs allow them to act both as mobile controllable loads and storage devices.

The expected usage of the EV as a transportation alternative to Internal Combustion Engine (ICE) vehicles is leading electric grid stakeholders to prepare the electric infrastructure to integrate their connection to the grid. In [5] several scenarios of car sales are considered for the period between 2010 and 2030, using the TREMOVE 3.3.1 model, where both electric and conventional ICEs are considered. When analyzing the sales of the EV types that are to be connected to the electric grid, like the Full Electric Vehicles (FEV) and the Electric Range Extender Vehicle (EREV) independently of the considered scenario, there is a noticeable increase of EVs to be handled by the electric grid as illustrated in Fig. 1.2.

The impact of EV integration in the operation and expansion of electric grids has been carried out in [6] with the evaluation of their impact in distribution networks. A quantification of the number of EVs that can be safely integrated in a typical distribution network is performed considering EV movement and exploring different charging locations in the grid. In [7] EVs are explored to provide ancillary services, namely in terms of primary frequency control, taking advantage of a local droop control mechanism embedded in the EV grid interface, and in terms of secondary control when integrated in an Automatic Generation Control (AGC) scheme. Additionally, the advantages of using EVs enhancing the integration of RES of intermittent nature have been explored. Since the management and control of EVs can have beneficial effects to the grid operation, both on technical and market perspectives, it is important to ensure that communications are able to support advanced control and management schemes.

The importance of communications in the future of distribution grids and in smart grid in general sets the theme of the work presented in this thesis. The underlying research question that this thesis intends to address is the identification of a communications architecture capable of coping with current and future control strategies. The hypothesis is that a careful design of the communications system will allow the smooth evolution of the distribution grid and facilitate the integration of new entities and new services. An active and scalable distribution network is expected to be better prepared for an enhanced integration

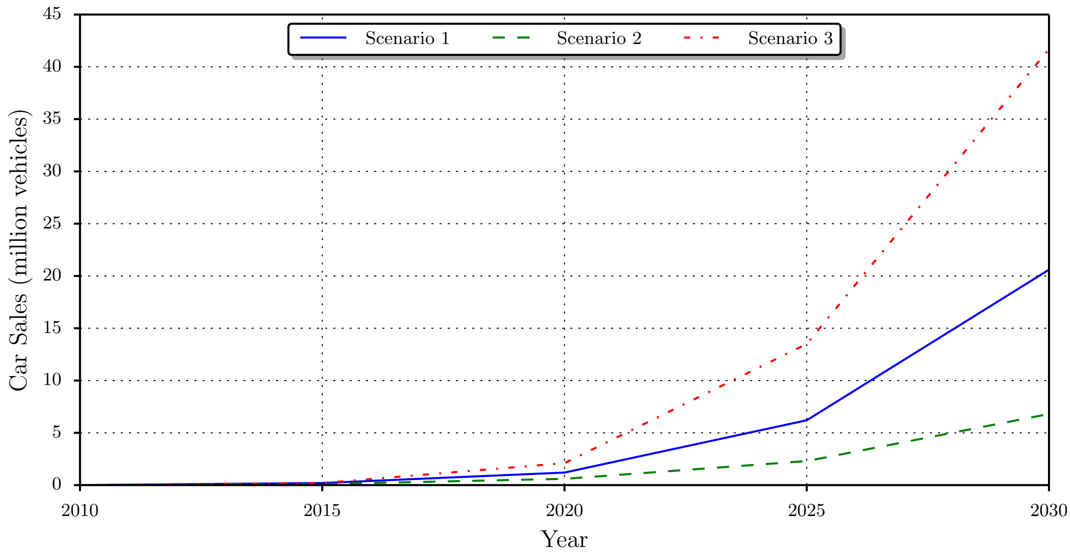



Figure 1.2: Sales of “pluggable” EV in Europe

of DER and in particular to deal with the electric mobility issues associated with the introduction and integration of EVs.

The benefits of a communications infrastructure designed for SG applications is associated with the ability to provide advanced technical and market operation. The support of enhanced control schemes and market oriented operation is deemed to have a positive impact on the electric network efficiency and reliability allowing the system to be better prepared overall to handle disturbance events. Even when these are severe, communications infrastructures can have a strong impact on supporting islanding systems, in ensuring higher survival indices and preventing cascading events. Communications systems can also have a beneficial impact on restoration schemes after a blackout event, allowing faster and coordinated recovery strategies to be explored.

## 1.2 Objectives

The exchange of data and control signals will allow the implementation of enhanced monitoring and control schemes, which will in turn require a communications network that is able to cope with the requirements imposed by the electric grid of the future. The distribution segment assumes particular relevance in this work because it is the center of the paradigm change introduced by smart grids. The main research issue of this thesis is related with the strategy and framework to consider when designing communications solutions for the future distribution grids, which needs to account for the smart grid paradigm change and the expectations of the different participants in electric power system. In order to address this the following main objectives where established for the work presented in this thesis:

- Identification and characterization of requirements that communications need to fulfill to enable enhanced control schemes envisaged for the distribution segment of SG;

- Definition of a functional and logical architecture to tackle the interconnection of power systems with communications systems accounting for technical and market operation perspectives;
- Identification and characterization of distribution networks in order to understand the number of potential communicating nodes and their geographical distribution;
- Analysis and assessment of the impact communications can have on overall performance of enhanced control schemes envisioned for the electric distribution segment in demanding scenarios;
- Evaluation of the feasibility of potential communications technologies suited for the last-mile segment of the electric distribution network;
- Assessment of the impact of uncertainty of communications in a near-real scenario through the use of a laboratory infrastructure to evaluate the operation of a microgrid under different conditions.

The stated objectives led to several contributions, which are identified and discussed at the end of this thesis.

## 1.3 Organization of the Thesis

This thesis is organized in seven chapters and several appendices, being this section the conclusion of the first chapter. In each chapter an introductory text is presented along with a highlight of the main topics to be covered and a final section summarizes the mains ideas and related conclusions.

The second chapter addresses the state of the art and related literature review. An overview of traditional power system operation and recent control strategies for LV distribution networks is provided, considering isolated operation and EV participation. The smart grids topic is presented with a detailed characterization of the problem of communications in power systems. Smart grid applications are presented along with the respective communications requirements. The importance of models and standards is emphasized as a key driver in supporting interoperability. Afterwards, topics such as architectural models, logical and physical segmentation of communications network in electric grids and candidate enabling technologies are discussed. The emerging solutions for distribution networks are identified along with associated routing protocols. Simulation tools are presented from the electrical and communications perspective and the main R&D projects in this area are identified.

Chapter three specifies an integrated model for smart grids with electric vehicles. The main involved entities in the electric and communications networks are identified and the mapping between them is established. Operation models and supporting information flows are identified. It is presented a specification of the communications infrastructure of an experimental laboratory deployed in INESC Porto premises aimed at concept validation, functional evaluation, and performance assessment considering both the electric and communications systems.

In the fourth chapter are approached the different methodological aspects related with the work developed in this thesis. A simulation platform is presented considering the integration of active DER in a distribution network. A dynamic simulation is performed along with the uncertainty introduced by the communications systems considering a high level perspective. Islanded operation is considered in a rural and urban distribution network establishing a demanding scenario in terms of system operation.

A method for the characterization of the Portuguese distribution feeders is proposed, including LV and MV networks, providing an enhanced context information upon which communications systems are to be installed. Candidate technologies considered for last-mile connectivity are evaluated in terms of performance and adequacy to SGs. The laboratory microgrid infrastructure is presented, along with the description of the electric and communications infrastructures and methodological aspects that allow the evaluation of different scenarios of operation.

Chapter five addresses evaluation aspects and results related with the developed work considering the respective methodologies described in the previous chapter.

The final chapter presents a discussion of the overall work developed in this thesis by analyzing the results and reviewing the main contributions achieved. Research aspects related with this thesis and the identification of future work and opportunities to explore close this chapter.

The appendices contain relevant and more detailed information related with specific topics addressed in different chapters of this thesis to support and give context to concepts providing complementary or summarized information. Each one of them is explicitly referred to throughout this thesis, when appropriate.

# Chapter 2

# State of the Art and Literature Review

## 2.1 Introduction

The work developed under this thesis covers several areas of research that spread from electric power systems to telecommunications. The state-of-the-art presented in this chapter intends to provide a comprehensive overview of the related work, identified in the literature that approaches smart grid advanced control schemes towards the integration of Distributed Energy Resources (DER), like Renewable Energy Sources (RES) and Electric Vehicles (EVs) and communications solutions targeted to support SG applications.

This chapter is organized as a set of sections that separately address a number of relevant topics in the context of smart grids and that constitute the framework for this thesis:

- Power Systems - the operation and control is present from a functional perspective;
- Control Strategies - for distribution systems are presented considering microgrids and multi-microgrids distributed control schemes;
- Electric Vehicles - are introduced as specific DERs with high impact on distribution grids and a new mobility paradigm that will allow a more dynamic service exchange;
- Architectural Models - targeted for SG are presented, starting with the remote/smart metering approach as the basis for the general models defined by different entities;
- Technology Overview - is presented focusing on the potential candidates likely to provide the necessary infrastructure for the information exchange in the distribution grids of the future;
- Simulation Tools - approaching the tools typically used in this scope;
- Related Projects - where relevant contributions to the theme of this thesis are identified.

## 2.2 Power Systems Operation and Control

Power systems are in general large and complex systems composed of several interconnected segments at different voltage levels (HV, MV, LV), typically generation, transmission and distribution, where a balance between the supply and the demand is continuously sought. Their evolution has been relatively slow and coherent due to the importance of such a system in the society that requires a high degree of stability and robustness to ensure a safe and reliable operation; besides investments made in this industry usually represent significant financial efforts that need to be carefully considered.

The variety of phenomena associated with large power systems concerning steady state or dynamic behavior, can have time horizons that range from minutes to milliseconds. Their operation requires advanced control mechanisms to enable a reliable and economic feasible exploration of such systems. Hence, power systems are designed to operate and provide adequate and secure services to all participating entities under different conditions. There are several definitions regarding the electric power system operating conditions, which mainly differ in terms of the considered functional schemes associated with the different states. In [29] the system operation is divided into states according to the following characteristics:

- Normal State: Adequate generation is available to supply the demand and operation requirements are respected. The normal state can be further divided into secure and alert states depending on whether a likely event can or cannot potentially endanger the normal operation resulting in a transition from this state.
- Emergency State: Adequate generation is available to supply demand but operation requirements are not completely respected.
- *In-Extremis*: Generation is not adequate to meet the demand nor are the operation requirements respected.
- Restorative State: Demand is not completely met but operation requirements are respected.

A similar approach is presented in [30] where a functional state scheme and the respective events associated with the possible transitions of each state are described. The respective state diagram is present in Fig. 2.1.

The *Normal* state is defined as the one where system variables are within their specified ranges and there is no overload conditions on any equipment, with the system operating in a secure state without violating any of the constraints. In the *Alert* state the system security is affected, with a direct impact on adequacy, given the adverse operational conditions, for instance due to weather related occurrences. In this state the system variables are still within acceptable range and no restriction is violated, but any contingencies can have a more severe effect, which may result in more adverse operating conditions introduced for instance by an equipment overload event. The system enters the *Emergency* state after the occurrence of a severe disturbance has occurred when under alert, the system is still able to operate despite the incurred variations in system variables like bus voltages or equipment state of operation. The objective is to promote the return to the *Alert* state by deploying emergency control actions, which may include, among others, generation control, load curtailment or fault clearing. The *In Extremis* state is reached if the operating conditions are aggravated due to inefficiency of emergency actions or due

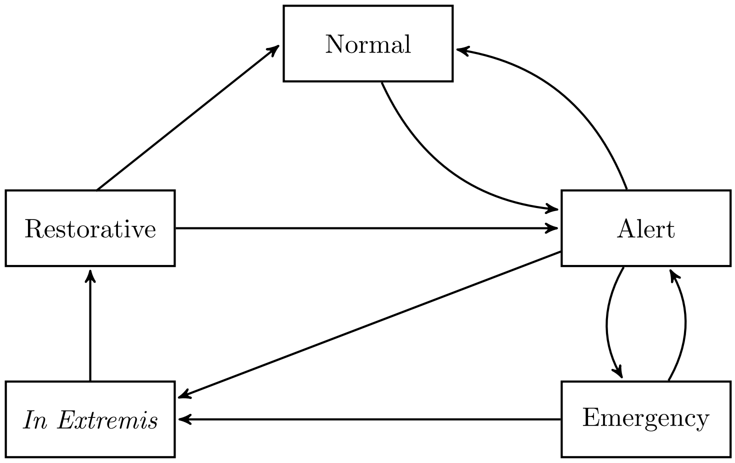



Figure 2.1: Power System Operating States

to other externalities that severely compromised the system when operating in the *Alert* state. The consequences of such extreme state may include cascading outages ranging from system isolation actions up to a generalized blackout. The *Restorative* state is defined as being the one where control actions are taken, after recovering from the extreme operational conditions, in order to bring the system to the *Normal* operation. The system may go from the *Restorative* to the *Alert* mode if, in the meanwhile, operating conditions are degraded.

Preventive, corrective, emergency and restorative actions are performed pursuing the normal and secure operation state. Any event that leads to or can potentially cause a state change outside the normal operation will trigger a set of control actions. While some of these actions are initiated locally, others depend upon a communications infrastructure to implement a remote control action issued from a control center. For instance primary frequency control is a fast and local control mechanism that causes a power variation proportional to the frequency deviation, like a governor system installed in generators. On the other hand secondary frequency control is managed by an AGC system that issues set-points to remote generating unit under its control area in order to guarantee the restoration of the frequency to its nominal value.

The reliability of power systems is a key issue, hence the need to conceive different states of operation that detail and differentiate control actions to be triggered. These states can be further detailed according to the complexity of each system and available control schemes. Nonetheless, it is impossible to ensure a fully reliable power system, as pointed out in [31], for several reasons. Among these are the large number of contingencies in modern power systems to be considered. Furthermore, the evolution of the electric grids along with the increase in complexity and the economic limitations when designing control systems to handle the wide variety of disturbances, will also have an impact on the overall system reliability.

The existing power control systems can be separated and summarized as follows [32, 33]:

1. Local Control - is a composition of systems where inputs are collected in a local area and control outputs are triggered in the same area, thus not requiring any remote communications infrastructure, involving analog or digital input/output.

   (a) Protection Systems Control - circuit breaking devices triggered by microprocessor based relays to ensure the protection of equipment and persons from faults. These devices require sensing capabilities to recognize the fault event, which can be due to high currents, frequency deviation and over or under-voltage, among other variables. These systems are required to operate within as little as a few milliseconds after the fault disturbance is detected, making it typically the fastest control mechanism;
   (b) Governor Control - is a control mechanism associated with electric generators, which adjust the power output according to a set-point by sensing and varying the mechanical shaft speed. The governor control is a form of primary frequency control that represents a very fast form of control. It can also respond to secondary frequency control set-points from AGCs;
   (c) Voltage and Reactive Power Control - consist in a mechanism to control the output voltage or the input reactive energy absorption within predefined ranges. In the case of generators, this system acts over the excitation circuit allowing the control of the voltage and reactive power. Tap changing transformers and switched capacitor banks are also used to provide voltage control. This is historically a slow control mechanism; however power electronic devices have been used to deploy fast voltage and reactive power control;
   (d) Power Flow Control - it is used to balance the flow of electricity according to the capacity of the grid lines, thus preventing overload situations from occurring. In AC transmission lines the power flow control has been historically implemented through phase shifting transformers, resulting in a slow control mechanism, but recently power electronic devices have been used, like FACTS, allowing fast power flow control;
   (e) Power System Stabilizer Control - is a supplementary control mechanism to generators in order to damp oscillations using local measurements.

2. Wide Area Control - is a composition of systems that require a remote communications infrastructure to enable the collection of inputs and triggering of control outputs pertaining to different areas.
   (a) Frequency Control - also known as secondary frequency control is a wide area control mechanism that deals with frequency deviations introduced by the imbalance between generation and load. To maintain the system frequency at nominal value a coordinated control needs to be performed between control areas. The Automatic Generation Control (AGC) entity is responsible for dispatching control orders (set-points) to generators after collecting relevant state information like frequency and power flows;
   (b) Voltage Control - similar to AGCs, these systems provide voltage control over wide areas to maintain voltage within predefined levels. Set-points are sent to local voltage controllers in a coordinated effort to mitigate voltage variations;
   (c) Special Protection Schemes / Remedial Action Schemes - are control systems specific of wide area that rely on dedicated communications links and computer infrastructures. Metering data from distributed sensors is collected and the values are used by control and protection algorithms. These schemes require fast deployment of different decision strategies along with

very high levels of reliability. The importance of communications infrastructures and the impact they can have on such systems represents a matter of concern and, as such, to minimize their impact, redundant communication links are used as well as decentralized strategies that allow distributing the computational and communication burden [34].

The importance of communications has recently begun to rise mainly due to the implementation of wide area control and protection schemes. The rationale behind using communications in wide area power systems applications has been straightforward. The vital importance of protection systems as the last frontier in ensuring a secure operation of the electric power system has dictated the use of dedicated communication and processing infrastructures. The remainder wide area control systems, like AGCs, have comparatively less stringent requirements and can rely on shared communications networks. Depending on the objectives of different control applications and respective requirements several communications technologies can be considered, which usually include PLC, microwave and fiber optic networks [34].

The integration of additional entities and devices, such as those associated with the genesis of the SG paradigm, will demand enhanced control strategies. Moreover the increasing complexity of electric systems, due to the incorporation of non-utility related participating devices driven by economic and environmental factors, allows for a very large number of contingencies to be accounted for. These can have a significant impact of security and reliability indices of the operation of power systems. The recent evolving nature of power systems has become a greater source of unpredictability, as opposed to legacy systems where designers and operators were used to fairly stable behavior patterns [31]. The use of distributed control systems has resulted from the segmentation of operational requirements of the electric power system and the need to relieve the computational burden of centralized entities and supporting communications means. These strategies are especially important in the distribution grid, which represents the segment where more changes are expected to be introduced. As will be pointed out, the interaction of hierarchical and decentralized structures with central control entities will require a suitable communications infrastructure to ensure the necessary connectivity requirements.

## 2.3 Control Strategies for Low Voltage Distribution Systems

The evolution of distribution networks will introduce more advanced control strategies other than those strictly required to ensure a proper operation. The legacy control architecture of electric networks relies typically on a rigid vertical hierarchy with the information being cumulative exchanged from the bottom to the top. As new elements are introduced in distribution grids not only are these networks expected to become more flexible but they also pose more challenges in conveying information in such a rigid architecture. Distributed architectures like a Microgrid (MG) enable distribution networks to adopt a cooperative strategy.

Microgrids represent an evolution of the distribution networks, which may act as active cells with additional control capabilities that can benefit the system operator as well as the end-user. These structures were thought to foster a higher penetration of DER in distribution grids while mitigating possible negative effects of such integration. As such, the main objective in the design of microgrids is the implementation of a management scheme for these resources ensuring the proper operation conditions of distribution networks in terms of quality and continuity of service as well as the maximization of RES penetration and high efficiency generators contributing to the reduction of $CO_2$ emissions.

### 2.3.1 Operation and Control of Microgrids

The microgrid concept was initially introduced by the US Department of Energy (DoE) within the Consortium for Electric Reliability Technology Solutions (CERTS). One research area of CERTS targets the reliability of electric systems and the integration of DER and, within this scope, the MG concept was defined. The underlying policy defined by CERTS of integrating DER was more ambitious than the typical "fit-and-forget" Distribution Generation (DG) visions until then. The MG was the first concept with an integration policy of DG and DER.

In Europe the MG concept was developed within the MICROGRIDS European project. The base concept is similar and it consists in a LV distribution network capable of integrating MG systems connected through power electronic converters with management and control functionalities [35]. In fact, a MG is a LV feeder which has a portfolio of devices such as microsources (e.g. PV, micro wind generators, fuel cells, microturbines, storage devices, etc.) and controllable loads managed by a hierarchical control system supported by a communications infrastructure, as illustrated in Fig. 2.2.

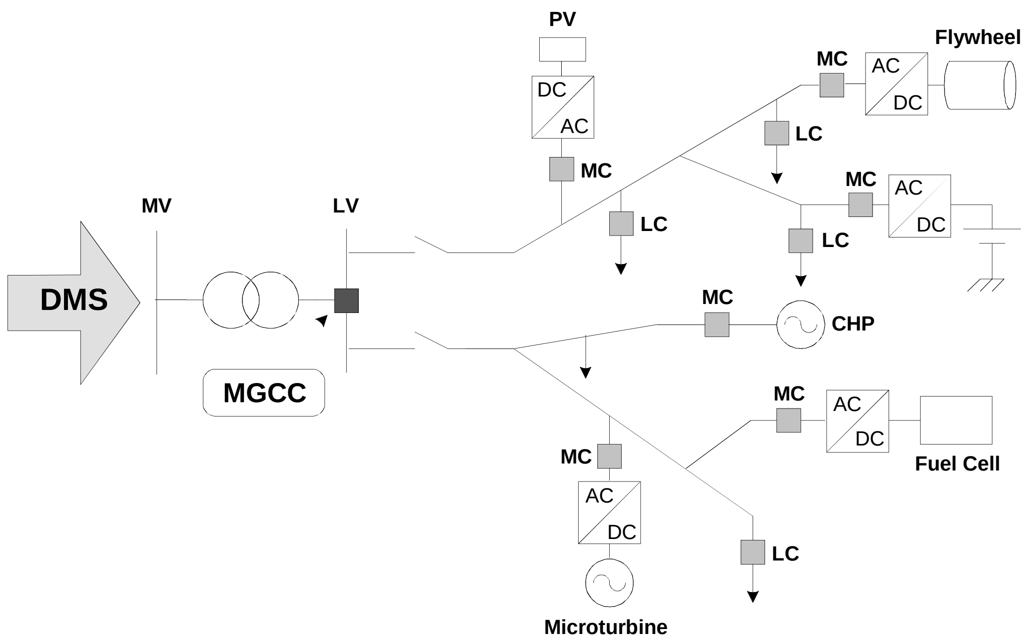



Figure 2.2: Microgrid Control and Management

The MG, defined in MICROGIDS project, has a hierarchical control structure that includes different controller entities that interact through a communications infrastructure. The controllers can be classified into [36]:

- Local Controllers - These are active control interfaces for: microsources, which are micro-generation units of active and reactive power; controllable loads, individually or in group. These controllers are the lower level elements in the hierarchical control and they are responsible for the interaction with higher level elements when required. They can be divided into Microsource Controllers (MC) and Load Controllers (LC).

- Microgrid Central Controller (MGCC) - This controller is located at the level of the MV/LV secondary substation and operates in the low voltage segment where the microgrid is formed. It is responsible for a variety of functions within the microgrid that range from power flow monitoring up to enhanced technical and economic management of the microgrid operation and the implementation of optimization schemes. The MGCC can issue control set-points to local controllers and is also responsible for the interaction with the higher level element.

- Distribution Management System (DMS) - This is the top level controller of the MG structure being responsible for the control of several MGCCs with which it exchanges control and management data.

An MG active cell is very flexible and is able to operate in two modes [37]:

- Normal/Interconnected Mode - the MG is connected to the main MV network while consuming or supplying electric energy (importing or exporting) depending on the technical conditions, available generation and existing load consumption, and on contractual conditions defined with the system operator. In this mode the MGCC is able to optimize the MG operation by issuing control set-points to local controllers and collecting metering and monitoring data. Applications such as demand side management are thus implemented in a distributed fashion. In order to implement technical and economic operation the MGCC can have module such as: short-term prediction for load consumption and local generation capacity; economic dispatch; DSM and others;

- Emergency/Isolated/Islanded Mode - the MG operates autonomously disconnected from the MV network due to a failure event or a planned action; the transition can take place seamlessly or be part of a restoration procedure. Depending on the severity of the disturbance the MG has a certain probability of survival, in which it is able to continue to operate isolated from the upstream network like a physical island. The emergency operation is sustained due to the immediate and continuous action of local controllers where the MGCC manages the state transition and can only resume the optimization schemes once the system is balanced. In case the islanded MG is not able to sustain its operation after a disturbance, for instance due to a generalized system collapse, it may be possible to explore the MG characteristics and its potential to perform a local system restoration. This allows the MG to resume operation minimizing the downtime of the local electric system without having to wait for the upstream disturbance to be cleared. A distributed system restoration scheme allows the distribution grid to take advantage of microgrids to facilitate the overall system recovery although the re-connection of restored MGs may raise some additional challenges. The restoration procedure within the MG is supervised by the MGCC that is able to exchange set-points with the local controllers to ensure system recovery [38].

### 2.3.2 Microgrid Communications

The MG hierarchic control structure requires a communications infrastructure to allow the MGCC to coordinate all the elements under its control. The MGCC must be able to exchange data with the local controllers for supervision and control allowing the implementation of optimization schemes. Data exchange may include active and reactive power values, voltage levels or state of control switches, considering a limited geographic range. Requirements concerning data exchanged within a MG are low in terms of bandwidth because mainly set-points are exchanged. Local controllers are the control elements that have to react rapidly to system disturbance whereas MGCC has a more relaxed operating mode, which poses little constraints in terms of communications latency [4].

Given that communications within MGs are not very demanding and costs have to be contained, as such narrowband communications systems can be considered. In MICROGRIDS project Power Line Communication (PLC) was suggested as a candidate technology to support MG communications infrastructure [39]. An assessment concerning the physical communication channels was conducted, considering signal attenuation, interference, noise, distortion, data integrity and reliability. TCP/IP was pointed out as the preferred protocol stack due to its flexibility and scalability properties, allowing the interconnection of MG devices independently of the lower layers (network technologies) and supporting future expansions of an MG or the interconnection of several MGs.

## 2.4 Control Strategies for Medium Voltage Distribution Systems

The high penetration of microgeneration systems, storage devices and controllable loads may lead to the establishment of several different microgrids in the same geographic area supported by a common MV distribution network. Considering this premise an extension of the Low Voltage (LV) Microgrid concept was introduced by the Multi-Microgrid (MMG) concept defined at the MV distribution grid. An MMG is a higher level structure that aggregates MGs, DG and loads at medium voltage. This level of aggregation introduces new challenges in coordinating several MV distributed elements.

The considerable complexity found on distribution networks can lead to the need to control and coordinate a significant amount of MGs along with MV loads and DER. Hence the MMG concept has been developed within the MORE MICROGRIDS EU project where control strategies were defined to enable the operation of multiple microgrids and the integration of DER using communications systems [40].

### 2.4.1 Operation and Control of Multi-Microgrids

An enhanced hierarchical control architecture like the one proposed in [41] can be used, where a MV controller is responsible for the management and control of the MMG under the supervision of the Distribution System Operator (DSO). This controller is designated Central Autonomous Management Controller (CAMC) and acts as an interface for the DMS for a particular MV network. The MMG control and management scheme is illustrated in Fig. 2.3, from [41], where CAMCs under the supervision of the DMS manage and operate MV feeders by exchanging information with DG, MGCCs and other elements.

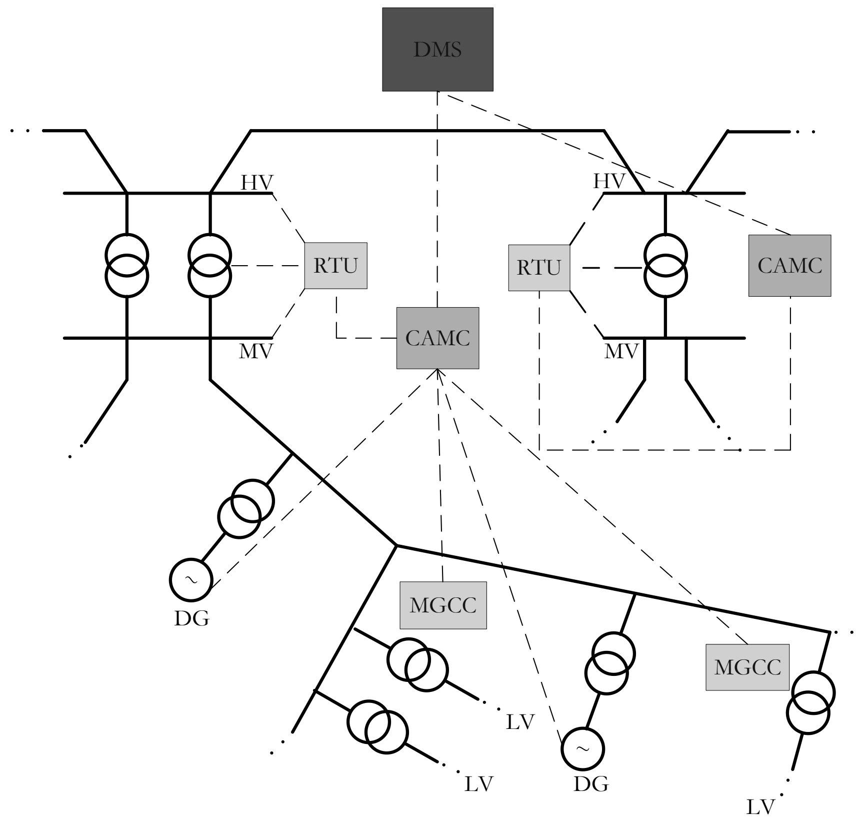



Figure 2.3: Multi-Microgrid Control and Management Architecture

The CAMC is responsible for the management and control of all distributed elements in the distribution networks at MV level with which it exchanges command set-points. It interacts with MGCCs, however, without having detailed information of each MG. The internal control of each MG is carried out by the respective MGCC, being the CAMC a higher level coordination entity. In fact the control hierarchy of a MMG can be divided in three different levels of control [36] as illustrated in Fig. 2.4:

- Level 1 - Headed by the DMS that supervises the entire distribution network by managing and controlling lower level entities;
- Level 2 - Composed of several CAMCs installed at the HV/MV substations, they are responsible for the interaction with entities operating in MV bus. Like SCADA systems, CAMCs interact with Remote Terminal Units (RTU) to collect monitoring data;
- Level 3 - Composed of controllable devices directly connected to the MV level, which may include MGCCs and respective MGs or devices like MV DGs and loads, On Load Tap Changer (OLTC) transformers, Static Var Compensators (SVC), capacitor banks or storage devices.

The different levels in a MMG control structure allow a decentralized approach in which controllers can operate autonomously or participate in a coordinated control scheme. The computing effort in this kind of structures is lower since a given level only has to process the control requests from the upper level, being the control implementation restricted to its own level devices. The control schemes are hence said to be distributed in the sense that the CAMC does not directly control any of the LV devices of the MGs under its supervision.

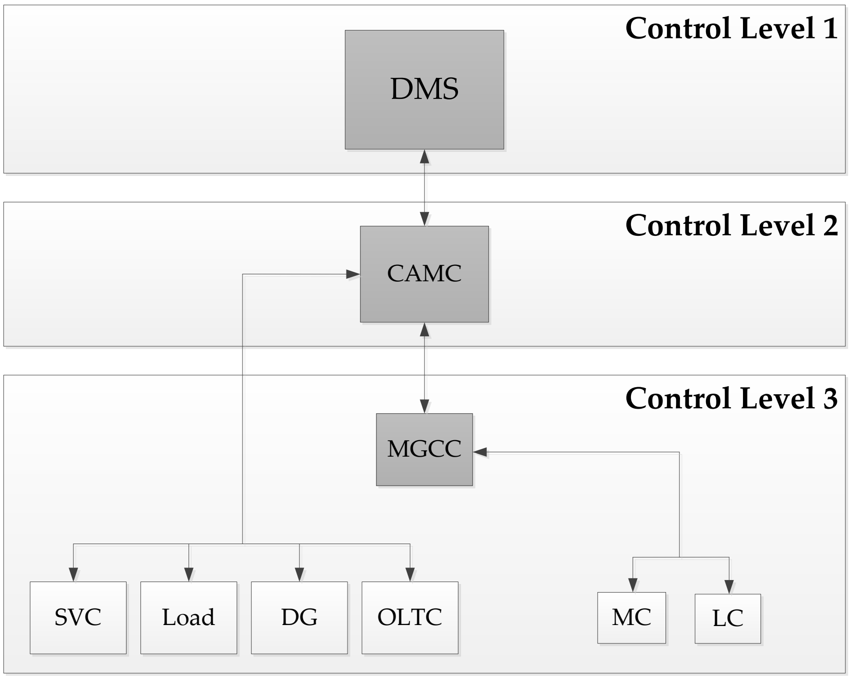



Figure 2.4: MMG Hierarchic Control System

Like in the MGs case, MMGs can also operate in two different modes:

- Normal Mode - the MMG is interconnected with the HV upstream network. In this mode the CAMC is able to manage the overall operation through the exchange of set-point with the MMG elements.
- Emergency Mode - the MMG is disconnected from the upstream HV network due to an isolation event (planned or unexpected). Depending on the characteristics of the MMG and the severity of the disturbance that led to the isolation, the MMG may survive and continue to operate as an islanded system. However, the MMG can also operate in emergency mode after a service restoration procedure (e.g., black start) enabling the system to start operating before the interconnection with the upstream network is fully functional.

Given the distributed nature of MMGs, some functionalities, usually associated with a DMS, can be implemented by the CAMC as the head of a MV distribution network, which can act as an intermediary or a proxy element. Hence, the CAMC is able to deal with both technical and market operation issues in managing and supervising an MMG.

A set of functionalities that can be associated with the CAMC were well established in [42]:

- State estimation - a local routine to estimate unknown parameters from measurements and commercial information to provide a complete and consistent model of the operating conditions of the

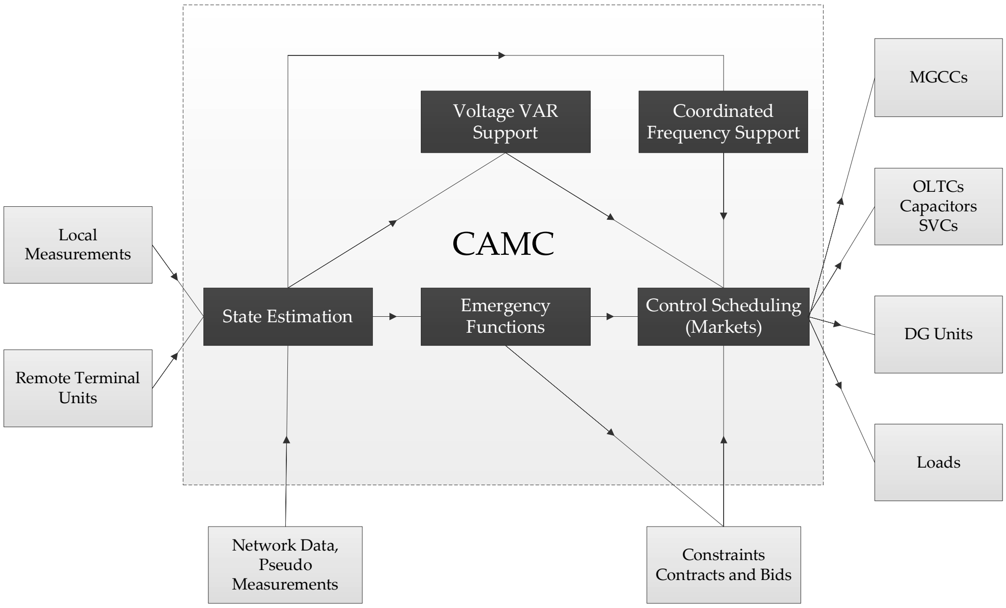



Figure 2.5: CAMC Functionalities Interactions

power system. This is the case of a typical DMS functionality. Nonetheless, it is regarded as a fundamental tool for the CAMC to provide state estimation data to the DMS and to other local functionalities.

- Voltage/VAR support - it involves the definition of voltage control areas and it allows the CAMC to control the power flow of different MGs and to optimize the global system operation of an MMG. Considering the typical three levels of control the voltage/VAR support can be discriminated as follows:
  - Primary voltage control - keeps voltage levels within predefined values in a control action deployed in seconds;
  - Secondary voltage control - maintains voltage profiles in a specific area while minimizing reactive power flows in a control action that it is supposed to be deployed in minutes;
  - Tertiary Voltage Control - targets optimal voltage profile and the coordination of the secondary control using technical and economic criteria in a control time-frame in the order of tens of minutes.
- Coordinated frequency control - it includes frequency control functions defined for both normal and emergency modes. When interconnected with the upstream network the MMG can participate in the primary frequency control since large DG units may be available. When isolated, the control schemes are limited to active power and load control, in particular load shedding strategies may be used to guarantee the MMG survival. The CAMC is able to also participate in the secondary frequency control as a reserve management entity. The management of the different controllers inside a MMG, like a MGCC, can allow the CAMC to guarantee the necessary secondary reserve.

- Emergency functions - including the control functions for islanded operation or system restoration (black start). The CAMC has the ability to intentionally trigger an isolation procedure, to ensure the survival of the whole MMG system or specific MGs. In case of system restoration, procedures can be initiated by the CAMC, which can have a beneficial impact in coordinating the MGs restored islands as the overall restore scheme progresses.
- Control scheduling - allows control actions based on energy markets for scheduling and dispatching activities to deal with variations in generation or consumption. The objective is to allow a more dynamic market operation and the introduction of new services aligned with the scope of MGs and MMGs.

The information interaction between the mentioned CAMC functionalities is depicted in Fig. 2.5 and further detailed in [36, 43].

### 2.4.2 Multi-Microgrid Communications

In order for the CAMC to operate it needs to have updated information regarding the devices and systems under its supervision to evaluate the MMG operating conditions. This information can be sent on a periodic basis or by request from the CAMC. The information exchange between the constituent elements of an MMG, mainly regarding active power and frequency control, are explained in Fig. 2.6 [36].

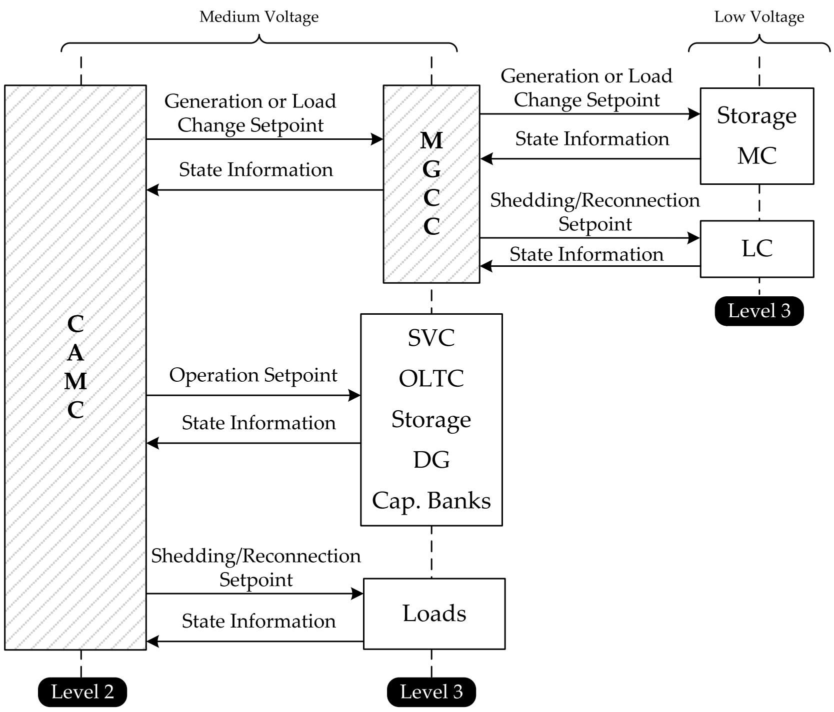



Figure 2.6: MMG Information Flows

The data exchanged within the MMG control structure relies on a communications to implement the different control schemes. However the availability and reliability of the communications infrastructure is very important since some control actions have stringent requirements and issues like delay variation or even data loss can have a negative impact on the management and control of MMGs.

## 2.5 Isolated Operation

The isolated scenario represents a highly undesirable form of operation by system operators. In fact, the control structures are currently not prepared to handle such form of operation and typically the available DG and other DER are just disconnected in the occurrence of such event. There are however reasons behind this rationale: the difficulties in guaranteeing the isolated system security; the fact that the protection schemes need to be altered due to a topology change and reversed power flows; challenges in maintaining system voltage and frequency values mainly due to the absence of controllable conventional synchronous generators.

Despite the specificities of distributed generators their integration in electric networks became possible with the adoption of power electronic devices, in particular through the use of DC/AC or AC/DC/AC converters/inverters. Hence, it became obvious the importance of controlling the operation of DG units through their inverter coupling modules [37]. Their usage has been recently envisaged for islanded/isolated systems either to ensure a system stability even during islanding transients or as a support mechanism for system restoration procedures after a blackout event.

In [44] the autonomous operation of a microgrid system after an islanding event is investigated, taking into account the benefits of including DG in the isolated system control and considering the presence of a conventional synchronous generator and generating unit equipped with a P-Q control. Protection schemes and islanding detection are among the main issues raised when considering an islanded transition. In [37] similar concepts are explored but considering DG units interconnected through Voltage Source Inverters (VSI) that act as synchronous generators, allowing voltage and frequency control defined according to the internal droop characteristics. Load shedding schemes are assessed within a secondary frequency control, in order to prevent the untimely and prolonged action of storage devices in stabilizing the frequency of the islanded system, given their finite capability to inject or absorb power.

The use of isolated microgrids in enhanced restoration schemes are investigated in [38] at the LV level. Voltage and frequency control strategies are evaluated using inverter control schemes and storage devices to ensure the necessary system stability and robustness of an isolated MG with the objective of reducing the restoration times after a blackout event, without compromising the power quality of the LV area or jeopardizing the recovery procedure. A similar rationale considering MMGs can be found in [45], where isolated MMGs are used for system recovery procedures. It is shown that the combined control of LV and MV DG units allows the restoration of MV networks, in a bottom-up perspective, considering several stages.

In isolated operation the requirements put over the communications infrastructure can be very demanding, even considering MG and MMG control structures. Their importance is critical in maintaining the system operation after an isolation event, ensuring the survival of the isolated network or in supporting a coordinated system restoration procedure when the isolated operation is compromised.

## 2.6 Smart Grids

In Europe the vision of the electric grids of the future, or Smart Grids (SG), is driving a paradigm change in what concerns the operation of distribution networks, by integrating large scale distributed generation, namely through microgeneration.

There are several definitions of the SG concept nevertheless a common notion is that it consists of an electricity network that incorporates advanced sensing and automation mechanisms, which are managed and controlled by central and distributed schemes supported by Information and Communication Technologies (ICT) [8]. As pointed out in [9] a single model for smart grids is unlikely, rather a multitude of approaches can be expected when contextual aspects are taken into consideration, like geographic and topographic characteristics, regulatory regime and the existence of legacy systems. Within the different visions, a coordinated and phased migration towards these novel electric networks is often identified as the main and common goal.

This chapter provides a general overview of the smart grid related concepts, detailing them particularly for the distribution segment in light of the context and evolution perspectives. The role of communications and related requirements for different operating strategies and applications are identified according to the vision of the main stakeholders. Finally the main models and standards related with SGs are presented.

### 2.6.1 Context and Challenges

The profound changes envisioned for the electric power system are being driven by several factors. One of them is the integration of distributed generation, in particular DERs that, besides generation devices, also comprise storage and responsive loads. This is particular important since in distribution grids there is an inefficient power storage, which introduces limitations in the support of network operation in dealing with intermittence of DG from renewable source. Another factor is the need for improving the operational efficiency and reliability of an aging infrastructure. This opportunity, combined with regulatory provisions, is being taken by utilities to meet environmental targets and consequent reduction of greenhouse gas emissions by incorporating renewable sources and implementing demand response programs [10]. The modernization process associated with these changes is turning electric grids into smart grids.

Technologies and applications are being used to prepare the distribution grids to cope with the expectations of different participants, enabling the implementation of features and functionalities to support the operation of the grid under new scenarios. This encourages system operators to invest in distribution networks, while deferring infrastructure investments focusing on grid efficiency and network reliability, in order to reduce operating and maintenance costs.

In [11] the key driver categories that are supporting the integration of DG within SGs are identified: environmental, commercial and regulatory. The environmental drivers are related with the need of limiting the Green House Gas (GHG) emissions, by incorporating renewable sources and reducing the need for additional electric infrastructures or large power plants. Commercial drivers are related with the large investments required to deploy large power stations that, in light of market uncertainties, favor the penetration of DG, since investments are low and thus represent a smaller financial risk. National regulatory bodies have acknowledged the need for a diversified generation portfolio and the advantages of having distributed energy sources closer to the consumption. This ensures enhanced energy security, driving the penetration of DG, which in turn will introduce competition in the generation segment with recognized benefits in terms of market dynamics.

The envisioned functionalities for SGs are regarded as an opportunity not only to implement enhanced management schemes but also to involve end customers, turning them into active participants in services exchange [12]. The advent of smart grids carries with it a set of key challenges related with the paradigm change mainly due to the new active nature of segments like the distribution, which were typically designed to be passive.

Recently, one of the biggest challenges for the electric grid has been the integration of intermittent resources, with wind power leading the growing segment within the renewable energy industry. Although solar generation solutions are also being deployed, investments are prevalent on wind technologies and both represent intermittent energy resources, which introduced challenges for electric system operators. The transmission segment has been planning network expansions to accommodate increasingly dispersed large wind generation systems and stability studies are constantly being carried out to determine regulation requirements and address long-term resource adequacy. The distribution segment has also been dealing with microgeneration integration, namely from renewable sources, which introduces new power flow patterns requiring protection and control schemes, enhanced distribution automation, microgrids management and control, among others, to ensure grid regular operation. In this particular case, DERs are considered to be a cost effective solution to improve power quality and reliability.

The progressive deployment of smart grid structures, intended to answer the challenges faced by traditional electric grids, also brought challenges of its own. Despite the different visions of the smart grid concept, a base notion is that it consists of a modernized and improved electric grid with an advanced communications network to support information exchange aiming at the improvement of grid technical operation, through monitoring and control strategies while promoting an advanced market participation.

The introduction of new devices like smart meters, which can also be regarded as gateway devices between communications networks of both customers and utilities, has raised other concerns like data integrity, security and privacy. They are units with processing, monitoring, control and communications capabilities and thus represent a considerable global investment to be made.

The communications networks and underlying technologies represent another challenge to tackle within SGs, since the use of a variety of communications networks makes the electric grid more prone to new vulnerabilities and exposure to malicious intents. The absence of a specific solution tailored to smart grids represents a matter of concern given not only the diversity of requirements but also due to the roll-out of solutions that may still need a thorough validation and maturation process. Data reliability is a matter of great concern given the high quality indices that are typically targeted by utilities in the provision of electric services.

Security, privacy and data integrity are other examples of sensitive challenges for the electric grid. The smart meter alone is pointed out as a potential source of malicious intents [13] perpetrated either by end users or by external persons with the intention to profit from the potential security vulnerabilities. For utilities and service providers one of the most attractive functionalities associated with smart grids is related with the ability to account for the energy expenditures of consumers in more detail. Smart meters are also regarded as a highly desirable tool for fraud detection by informing when smart meters are tampered to report misleading information. Hence data authenticity in smart grid services is crucial not only in economic terms but also for technical purposes. Privacy is also a topic under debate given the multitude of information that is available to be exchanged between different participants in SGs. Data can be collected beyond the strict necessity of a specific service and its use can leverage towards an economical benefit or other advantages.

Another obvious challenge associated with SGs lies in the schemes that allow customers to exchange services with other stakeholders of the electric power system. This also raises issues such as market participation and the potential introduction of newer entities that deal specifically with commercially related smart grid services. Whether the incentives for participation are found on more dynamic price schemes for energy consumption or through other types of compensation mechanisms, the fact is that customers have to be involved since they have an ultimate decision regarding their participation.

From the system operator side there are new functionalities that are considered very appealing within the SG concept, like "self-healing". This automatic recovery mechanism is triggered by unexpected fault events and must act as quickly as possible. In this case, challenges are posed in terms of fault detection and automatic reconfiguration, which along with distributed control strategies and through communications networks allow distributed control mechanisms to react quicker and nearer to the defect.

The evolution of distribution networks can follow different paths and it is coupled with the underlying philosophy of implementers; however it will have to deal with these and other challenges in implementing the aforementioned paradigm change introduced by smart grids.

### 2.6.2 Evolution of the Distribution Grid

Historically the operation of distribution has relied on manual and generally non-aware systems and only recently has begun to incorporate real-time sensing and control systems and to integrate data from different systems. Current Distribution Management Systems (DMS) are implemented through extensions of Supervisory Control and Data Acquisition (SCADA) systems typically found in the transmission segment. There are different applications that can be found nowadays in current DMSs [14]:

- Fault Detection, Isolation and Service Restoration (FDIR) - used to detect faults on a feeder section through feeder terminal units, which allows fast isolation and quick restoration mechanisms;

- Integrated Voltage/VAR Control (IVVC) - allowing the use of capacitor banks to reduce network losses and voltage profile optimization in normal conditions or voltage reduction at peak load condition through transformer tap settings;

- Topology Processor - an off-line tool to determine the network topology with an optional alarm handling feature;

- Distribution Power Flows - determines the distribution power flows and enables the detection of unbalanced load flows, feeding this information to other DMS applications;

- Load Modeling (LM)/Load Estimation (LE) - utilizes distribution network information such as transformer capacity and consumer profiles with real-time measurements to estimate and forecast operating conditions of feeders;

- Optimal Network Reconfiguration (ONR) - used for network reconfiguration, minimizing energy losses and keeping voltage profiles and load balance conditions in distribution feeders;
- Contingency Analysis (CA) - allows the analysis of scenarios to enable proactive or remedial actions;
- Switch Order Management - real-time operation tool to manage, verify and execute switching plans;
- Short Circuit Analysis (SCA) - an off-line tool to estimate impacts of fault events in the distribution network;
- Relay Protection Coordination (RPC) - checks the state of distribution protective relay in the distribution grids;
- Optimal Capacitor Placement / Optimal Voltage Regulator Placement - an off-line tool to determine the optimal location for both capacitor banks and voltage regulators.

The expected transformation of the distribution electric grids motivated by the introduction of DERs, in particular those of renewable nature, will allow end customers to generate and inject electricity into the grid. The distribution, which was designed as a consumption oriented operation, will have to deal with more complex power flows based on enhanced and elaborated rules and schedules. It is clear for the electric industry, in particular for utilities, the need for enhanced monitoring and control schemes, some of which with considerable real-time constraints to allow a secure and efficient operation of the grid. This will have impact on traditional DMS functionalities and applications. Advanced DMSs will be required with novel characteristics, such as those defined in [14]:

- Advanced Monitoring, Control and Data Acquisition - a more detailed characterization of the distribution grid variables is required and extended to segments near or down to the end customer, i.e. through AMI;
- Integration, Interfaces and Standards - to enable the introduction of advanced applications by utilities and operators ensuring the necessary flexibility and expansion capabilities for future upgrades;
- Enhanced FDIR schemes with multi-objective and multilevel feeder restoration strategies;
- Enhanced IVVC - with improved and more detailed information regarding the operating conditions of capacitor banks, tap changer transformers and general purpose regulator towards operational and cost-oriented optimization of regional schemes;
- Advanced LM/LE - where customer behavior is more difficult to forecast, especially when considering the integration of EVs, but can be smartly managed;
- Enhanced TP, DPF, ONR, CA, SCA and RPC - used more frequently with more detailed models considering an extension down to the end customer, including concepts like microgrids and customer generation devices, i.e. EVs, accounting for bidirectional power flows;
- Increased data exchange and databases - to deal with more information from more devices and more complex models with regional and geographical representation to allow a more detailed and up to date perspective on the operational state of the network;

- Analytical and visualization tools - to track the performance of distribution grids and related smart-grids schemes from the perspective of electric network operators and end customers. They will enable the adherence to smart grid policies and incentives for the exchange of services towards common benefits;
- Enhanced security - represents an important feature transverse to all communications segments, applications and user access, to allow a secure data exchange.

Besides the evolution of DMSs, from a technical perspective the distribution related systems are expected to integrate even further the market oriented perspective. This integration between technical and market operation is becoming increasingly important since it allows the participation of new stakeholders and enhance the interaction among all SG participants. In the market environment it is expected that competition will grow, allowing more efficient forms of operating the electric grid, mainly due to the diversity of participating entities. The evolution of the distribution grid market operation can potentially allow customers to participate in ancillary services, through market representatives.

### 2.6.3 The Role of Communications

The electric infrastructure has been constantly evolving to adapt to geographical and demographic changes and has integrated new technologies and applications. In the last years these changes have taken place in the transmission and distribution segments, especially in those closer to end consumers where the electric energy is typically supplied with limited or no information feedback.

The smart grid concept incorporates different visions and strategies towards the modernization of the electric industry in providing high levels of robustness, adaptability, flexibility, security, economy, self-healing, and protection while supporting increasingly dynamic systems. This vision, in part, is possible with the use of communications networks associated and integrated with the electric power systems. Communications infrastructures are thus regarded as the necessary support for the information exchange to accommodate services and functionalities with different requirements in what concerns data rates, delays and losses among many others. The information exchange allows consumers to become part of an active network, where this data can be used for their own benefit and for improving the grid operation. The recognized advantage of having a wide market offer of solutions and equipment from different manufacturers will nonetheless require standardized approaches to enable not only equipment but also system interoperability and to facilitate the evolution of the smart grid based on flexible and scalable solutions.

Communications in smart grids are also expected to enhance the integration of devices like microgeneration, storage and responsive loads in a simple and fast approach inspired by the *Plug-and-Play* concept usually found in other areas. This allows energy resources to become available to customers/owners as well as to utilities or even market representatives, being the management and control dependent on the involved entities and related data exchange models, and the available communications solutions.

From a technological point of view communications can be based on either wired or wireless solutions that can coexist on the same or in different segments such as access, back-haul, backbone, etc. In fact, different technologies are already used in AMI systems that can be regarded as the initial stage of the expected evolution of communications systems for electric grids.

From the consumer perspective the presentation of data in a clear and functional way increases the awareness of energy expenditures, allowing the exploration of more dynamic and advantageous solutions that can go from a local management of resources up to a market oriented participation. In this case, awareness is precisely one of the key drivers that can stimulate the participation of customers in other areas with the proper support of communications.

From the grid perspective the importance of communications infrastructures is increasing due to the need to support enhanced control schemes which are envisaged to have a considerable impact on the network operation in terms of reliability, efficiency and security. The integration of communications solutions that enable the bidirectional data exchange will support management and operation strategies considering different modes of operation of the electric grid.

The interaction of different players like utilities and end customers is set to occur mainly at the distribution level. As already mentioned, this segment has been relying on minimal communications solutions mainly due to historical reasons, but they are now regarded as an important factor to stimulate SG applications. The selection and evaluation of potential communications solutions needs to be coupled with a detailed characterization of different distribution grids.

### 2.6.4 Communications Requirements

The definition of requirements for smart grid communications is not a consensual topic and there are some reasons behind this fact. The first one is due to the innovative nature of the topic itself where some concepts are still under evaluation because the associated advantages are still unclear for system operators, namely in terms of a cost-benefit perspective. Different interpretations of the SG functionalities and services are also subject of discussion between utilities and regulators, which translates into different views of requirements. Another reason can be associated with the technical difficulties when implementing specific communications solutions in particular scenarios, which highlighted the limitations that the selected communications technologies can have when dealing with SG applications.

A considerable challenge for the communications infrastructure within smart grids is associated with the large number and diversity of devices to interconnect and the different applications (current and future) to support. Moreover, it must also ensure that the electric power system is able to operate within the recognized stringent expectations in terms of reliability and security. In fact, if critical QoS requirements are not met, the performance of communications solutions deployed in SGs can adversely affect the system operation. Particular attention is also given to the support of different types of services by data networks.

The uncertainty surrounding the SG functionalities and services has a direct impact on the definition of the requirements and consequently on the analysis regarding the performance targets that communications should meet. The definition of requirements by the different regulation and standardization bodies can constitute a sort of wish list with contributions from different stakeholders to meet the expectations in the short and long-term operation scenarios from technical and market perspectives. The challenge is then in quantifying these requirements knowing beforehand that generalizing them is not straightforward nor consensual.

Throughout the different implementations of SGs envisioned worldwide, the initial definition of requirements for smart grid applications is invariably associated with the specification of functional requirements for smart metering and AMI systems. The importance of these systems was emphasized by the M441 mandate issued by the European Commission for smart metering applications where a set of functional requirements for smart meters were defined [15], concerning five different domains: customer, grid and network support, supply commercial aspects, security and privacy, and distributed generation penetration.

Recently, more functionalities have been specified for SGs, namely for the distribution segment, which involved different systems and entities. As such, it became evident that an effort had to be carried out involving several stakeholders of the electric industry in quantifying the requirements that communications networks should ensure, considering different scenarios of application, of which smart metering is only one of them. Another strategy was also considered for quantifying the communications requirements, which involved their analysis considering substation operation and related applications like those defined in the IEC 61850 family and in IEEE 1646 [16].

Given the importance of this topic several research project, workgroups and entities have been involved in the process of defining requirements for smart grid applications. The classification often depends on the type of application and the specific segment on the electric power system they intend to address. The next subsections present some visions regarding the quantification of requirements proposed by different entities or groups.

#### 2.6.4.1 OpenNode

OpenNode was an European project that continued the work developed in the OPEN meter project that focused on smart metering. OpenNode defined new functionalities and communications infrastructure beyond smart metering, by interconnecting the distribution substations with the end customers and the back-haul communications systems of utilities defining an OpenNode segment. Within the project scope, new functionalities directly related with smart meters were installed in customer premises towards advanced monitoring and automatic operation strategies for LV and MV distribution grids.

The project established the general communications requirements along with an architecture considering different interfaces, data models, security and candidate technologies, for the established OpenNode segment. This segment is equivalent to the access communications network or last-mile as usually designated in the literature. The considered communications interfaces that were specified in the project are depicted in Fig. 2.7, along with different data flows exchanged between the different nodes that compose the OpenNode segment.

Table 2.1 presents the estimates for bandwidth and maximum delays for communications between the participating nodes, according to the project vision.

#### 2.6.4.2 NIST

The National Institute for Standards and Technology (NIST) has been active in the area of smart grids mainly in what concerns standards and interoperability. It created a Smart Grid Interoperability Panel (SGIP), involving public and private partners from the electric industry, with the purpose of defining the requirements and specifications for the development of SG standards and solutions. The collaboration

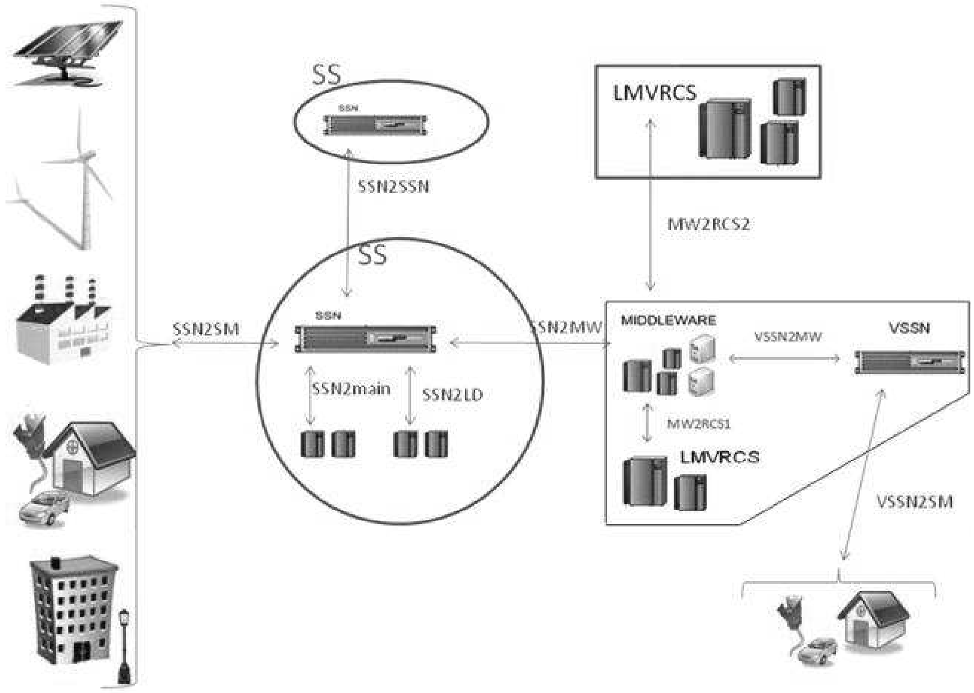



Figure 2.7: OpenNode Communications Interfaces and Data Flows

Table 2.1: OpenNode Communications Requirements

| **Segment** | **Bandwidth** | **Maximum delay** |
|---|---|---|
| SSN-SSN (inter-SSN) | 100kbps / 1Mbps | a few seconds |
| SSN-SM | >2.4kbps | [1s, 2s] |
| SSN-MW | >100kbps | [1s, 2s] |
| SSN-Local Devs | >2.4kbps | [10ms, 1s] |
| SSN-Maintenance Devs | tens of Mbps | several seconds |
| VSSN-SM | >2.4kbps | [1s, 2s] |
| VSSN-MW | >1Mbps | [1s, 2s] |
| MW-LVMRCS int. | >1Mbps | <1s |
| MW-LVMRCS ext. | >100kbps | [1s, 2s] |

and participation of the general smart grid community has been stimulated through Priority Action Plans (PAP) promoted by NIST to deal with challenges and specific objective of SGs. Information related with these PAPs is publicly available in the NIST website[1].

PAP-01, entitled "Role of IP in the Smart Grid", deals with the use of the IP stack in SG communications. One of the outcomes achieved by this PAP is RFC 6272, which addresses the components of the IP suite as a support for smart grid applications [17]. The use of IP based technologies in particular for Network and Transport layers was deemed as appropriate for the needs of smart grids. Another impor-

[1] NIST PAPs - http://www.nist.gov/smartgrid/priority-actions.cfm

tant output from this PAP is the identification of requirements for different smart grid applications. The data flows among different actors are considered within each specific application where typical values for latency, reliability, data payload and others are established. Table 2.2 summarizes the requirements of the main application classes defined by the NIST collaborative platform, along with the minimum and maximum values for some of the parameters presented in [18], considering reliability, latency and data payload. According to [19], reliability is defined as the probability of success that an item has of performing a required function under stated conditions and for a period of time. The latency characteristic is defined as the overall data exchange time, which includes the processing time at sending entity, the transport and forward over a physical medium and the processing time at the destination entity. The payload size is an estimate of the raw data volume in bytes that the application requires without any specific overhead data or encoding schemes for payload reduction. This PAP is currently concluded.

Table 2.2: NIST Application Classes and Communications Requirements

| **Application** | **Reliability** | **Latency** | **Payload** |
|---|---|---|---|
| Remote metering | [90, 99.5%] | [5s, 4h] | [25 bytes, MB] |
| Smart Meters - Events | [98, 99.5%] | [30s, 4m] | [25 bytes, 278 bytes] |
| Customer Info - Messages | [90, 99.5%] | [5s, 1h] | [50 bytes, MB] |
| Price | [90, 99.5%] | [5s, 4h] | [25bytes, 100bytes] |
| Centralized Voltage/VAR Control | 99.5% | [1s, 5s] | [25 bytes, 500 bytes] |
| Islanded Distributed Storage (Batteries) | [98, 99.5%] | [1s, 12s] | [25 bytes, 150 bytes] |
| Demand Response - Direct Load Control | [90, 99.5%] | [5s, 4h] | [25, 100] bytes |
| Demand Side Management or Demand Response | [90, 99.5%] | [1s, 1s] | [25bytes, MB] |
| Fault Clear, Isolation, Reconfigure | [90, 99.5%] | [1s, 5s] | [25, 50] bytes |
| Outage Restoration Management | [30, 99.5%] | [5s, 20s] | 25 bytes |
| PHEV | [90, 99.5%] | [5s, 4h] | [25, 100] bytes |

PAP-02, "Wireless Communications for the Smart Grid", is responsible for evaluating the advantages, disadvantages, capacity and constraints in the use of wireless standards for the lower OSI layers. Existing and emerging standards and related characteristics and technologies are considered according to the areas of application within smart grids. From the several achieved results, the creation of a functionalities/characteristics matrix with the target technologies for smart grids should be emphasized [20]. An adaptation of this matrix is presented in the Appendix A, considering candidate technologies for the distribution segment.

#### 2.6.4.3 US Department of Energy

In 2010 the US Department of Energy (DoE) issued a Request for Information (RFI) for the general participants in the electric industry in order to get feedback from a set of questions elaborated by the DoE which intended to assess the potential impact of the paradigm change introduced by SGs. From the collected answers the DoE elaborated a document containing the main communications requirements for the SG technologies. According to [21] the DoE, has categorized different applications for smart grids, which are listed in Table 2.3.

Advanced metering information applications are defined as those associated with the collection, metering and analysis for providing energy consumption data, outage notification and billing support to

Table 2.3: Smart Grid Functionalities and Communications Requirements from US DoE

| | Network Requirements | | | |
|---|---|---|---|---|
| **Application** | **Bandwidth** | **Latency** | **Reliability**[2] | **Security** |
| **AMI** | [10-100] kbps/node and 500 kbps in backhaul | [2, 15] s | [99, 99.99]% | High |
| **Demand Response** | [14-100] kbps/node | [500ms, min] | [99, 99.99]% | High |
| **Wide Area Situational Awareness** | [600, 1500] kbps | [20, 200] ms | [99.999, 99.9999]% | High |
| **Distribution Energy Resources and Storage** | [9.6, 56] kbps | [20ms, 200s] | [99, 99.99]% | High |
| **Electric Transportation** | [9.6, 100] kbps | [20ms, 15s] | [99, 99.99]% | Relatively High |
| **Distribution Grid Management** | [9.6, 100] kbps | [100ms, 2s] | [99, 99.999]% | High |

utilities and energy consumption data (current and historical usage), dynamic pricing information and DSM incentives to customers. From a technology point of view the communications requirements (e.g., bandwidth, delay, losses, etc.) for AMI are low and they can potentially contribute towards the implementation of HANs interconnecting all energy related devices within consumer premises, enabling in-home applications and the interconnection with utilities data networks. The technologies targeted for HANs are Wi-Fi, ZigBee and Homeplug. The same document mentions the generalized acceptance of IP based solutions by stakeholders along with its recommended usage in smart grids. This matches the assumptions and definitions of PAP-01 referred in the previous section.

The AMI concept defines also a communications segment outside the customer premises where information is exchanged between the smart meter and an aggregation point typically installed at the secondary substation. The requirements for this segment, according to the information collected by the DoE, is per node similar to the in-home HAN scenario. Although an increase in the data volume is expected due to the potentially high number of communicating nodes served by an aggregating unit. In terms of technology the preferred solution for this segment is PLC but the current constraints such as low bandwidth and the impairments introduced by distribution transformers to convey data upstream makes it suitable mostly for rural and low-density areas, according to some responses to the RFI. In fact the difficulties of PLC in supporting real-time AMI services is leading to the emergence of other solutions. In urban areas the use of RF solutions is referred to as a viable alternative and network topologies like mesh, star or radial can potentially ensure the necessary information exchange infrastructure in different scenarios. Other alternatives are also regarded as feasible like WiMAX, broadband PLC or cellular solutions. The backhaul is considered to be implemented by private networks (fiber, T1 or microwave). The provision of real-time and user discriminated services is regarded as big concern since it can lead to unfeasible bidirectional communications requirements. As such data aggregation strategies can be employed along with distributed control schemes to unburden the communications networks. One of such cases is the aggregation of customer related data to be conveyed upstream to the utility control center;

[2]It should be noted that this term is derived from the electric system reliability definition, but it is associated with what is commonly defined as service availability. This term is often found in the literature hence it will be loosely used in this thesis pertaining to the availability characteristic of communications networks.

whereas downstream control data can be sent from control centers to end customers without discriminating actions over specific equipment or systems leaving that decision to the home controller or HAN manager.

Demand response (DR) is considered as an application implemented at wholesale level by system operators and at retail level by utilities. The retail DR can be implemented through direct load control schemes in which customer electricity consumption is curtailed or through automated DR that responds to dynamic operating condition of the electric grid. The DR is an incentive based operation mechanism where, for instance, dynamic pricing can leverage the consumer willingness to participate in services to the grid. As such, the communications requirements of DR can vary significantly depending on how complex the control scheme is and on the intended purpose. Although bandwidth requirements for DR are similar to AMI and DR applications will likely be used together with AMI applications, the latency can be more stringent for DR, as illustrated in Table 2.3. Latency can have a significant impact if DR is used in emergency situations; however, it can also be used in cases where non-critical response is required. The technologies targeted for DR are similar to those of the AMI case as pointed out in [21]. The prevalence of broadband technologies, cabled or wireless, is regarded as an opportunity to support time-sensitive applications.

Wide Area Situational Awareness (WASA) makes use of several technologies to support monitoring and control of power systems over large geographical areas, with very demanding communications requirements in terms of data collection periodicity and data volume. Functionally WASA can be further divided into Wide Area Monitoring Systems (WAMS), Wide Area Control Systems (WACS) and Wide Area Protection Systems (WAPS). WASA is recognized as an increasing need in SGs, given the interconnection of different entities and devices and their interdependency. Information exchanged between different neighbor areas can help in preventing cascading problems and enhancing the technical and economic operation, helping system operators with a more detailed assessment on grid operating state. The incorporation and wide usage of Phasor Measurement Units (PMU) in electricity grids enable voltage and current phasor data to be available to system operators. However, these devices require high frequency readings over large areas to provide an aggregated snapshot of the electrical system. The data collected from PMUs can be aggregated and exchanged with central control systems. As referred to by RFI participant responses the requirements for WASA real-time operation will demand very low latency although it is also recognized that for post-event operation the latency can be higher. Given the specificities of these systems the candidate communications technologies are all broadband based, such as fiber optics, microwave or Broadband over PowerLine (BPL).

The integration of DER and storage is pointed out as a desirable application for SGs, where renewable energy sources, electric vehicles, combined heat and power, and other sources are integrated in the electric grid. Independently of the scale of DER, reliable communications are needed for monitoring and control. The vision of some (DoE) RFI participants is that DER will be able to participate in generation control schemes with modest bandwidth requirements but with very demanding latency as highlighted in Table 2.3.

The electric transportation application, also designated as electric mobility, concerns the large-scale integration of EVs as very specific DERs. On one hand the opportunities for these devices in providing services to the grid is highlighted by RFI participants. On the other it is stressed the impact that EVs can have since a considerable power consumption increase is to be expected, which may represent the equivalent of two additional domestic customers. The communications interoperability is pointed out as an especially relevant requirement due to the mobility characteristic of EVs since they are likely to be connected in diverse locations: at home, in parking lots, at work, etc. The bandwidth requirements can vary according to the type of exchanged data. For example, metering, billing or load balancing may require lower bandwidth when compared to the case of EVs participating in demand response schemes. The technologies targeted for electric transportation application are in-home network related, such as those presented in the AMI case, when the EV is in the customer premises.

The distribution grid management applications, such as distribution automation (DA) allow utilities to monitor and control devices in the distribution network to help in decision-making, enabling effective fault detection and power restoration. It includes distribution management systems such as SCADA and automation field equipment like reclosers, breaker switches, capacitors and transformers as Remote Terminal Units (RTU) or Intelligent Equipment Devices (IED). The communications requirements identified in responses to the RFI concerning DA applications are among the most demanding, with very low latency values. There are however somewhat less stringent DA requirements in cases like alarms and alert communications, but still considering a time horizon below one second. Some implementations of DA over an AMI communications network are considered by some participants in the DoE RFI. Nevertheless, wireless based technologies and in particular mesh and cellular solutions are also considered as possible alternatives. A particular distribution grid management application is substation automation. It concerns SCADA systems that require low bandwidth and low latency and, as such, they are usually implemented over fiber optic or wireless technologies given the hazardous electric environment.

### 2.6.5 Interoperability and Standards

The goal of a secure, reliable and efficient electric grid is directly associated with the communications infrastructure. In SGs the integration of different elements and components requires a syntactic and semantic interoperability approach besides the interoperability at the communication network level. The use of standards enables a common semantic (data model), a common syntax (protocol) and a common network concept [22].

Given the considerable amount of standards applicable to the smart grids concept and others being crafted specifically for SG applications, a classification of standards according to their domain and purpose is necessary. The Grid Wise Architecture Council (GWAC) defined eight interoperability categories, known as GWAC interoperability layer model, relevant for generation, transmission and distribution segments. These layers are distributed over three main categories: organizational, informational and technical, as depicted in Fig. 2.8 from [23].

Within the technical category it is possible to match communications standards to different interoperability layers as proposed in Table 2.4 for smart grid applications. In terms of basic connectivity the identified standards span from wired power lines to wireless license and unlicensed alternatives, somehow anticipating the support for different applications and communications network segments.

In 2011 the European Standards Organizations (ESOs), composed of CEN, CENELEC and ETSI, issued a set of recommendations concerning the standardization for smart grids in Europe [24] involving several areas. Standards are recognized as an efficient mechanism to promote EU industry cooperation

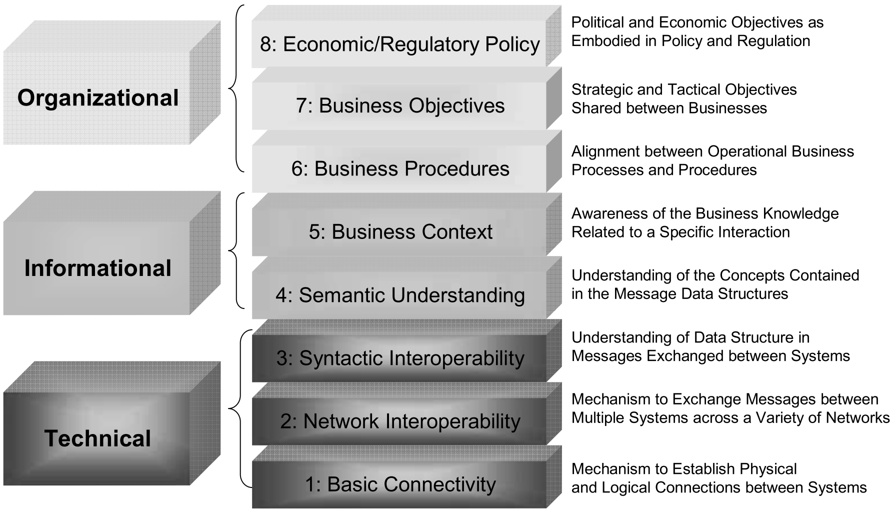



Figure 2.8: GWAC Interoperability Layer Model

and interoperability by allowing the accommodation of existing and novel solutions; general recommendations identified the need to focus on product requirements and promote standardization activities on interfaces instead of applications and solutions. The need for a reference architecture is highlighted and recommendations are made concerning: a conceptual model to define the interaction between stakeholders; a functional architecture based on the IEC/TC57 model to tackle both general and specific aspect of European smart grids; a communications architecture that defines the different connectivity scenarios and networks. Recommendations are further detailed considering communications interfaces with suggestions for: an interaction between different domains, particularly between AMI systems and other SG subsystems; a harmonization at data transport level; and further development of power line communications. The IEEE 1901 is pointed out as the broadband standard to be considered as an alternative to existing similar European standards.

The European Commission has issued a mandate to ESOs, the M/490, related with standards to support the deployment of a European smart grid. As defined in [25] the objective is to address standards for SG within the European framework toward the integration of communications technologies with electrical architectures, considering the associated processes and services. The expected deliverables include a technical reference architecture, with the functional information data flows between domains and systems, and a set of standards, which include communications protocols and data models. One particular aspect raised by the mandate is the large scope of smart grids and it emphasizes the risks of inconsistencies since too many standardization bodies will address related SG topics.

Recently, the ESOs have released the first set of standards along with a reference architecture as the initial work of the objectives established for the M/490. This list [26] is a general selection guide of standards targeting different systems (domain, function and other) and layers (component, communications and information) considering the Smart Grid Architecture Model (SGAM). This reference model was defined over the GWAC interoperability categories. The methodology used to present the smart grid related standards consists of mapping them into the SGAM reference architecture, where some cross-cutting do-

Table 2.4: GWAC Technical Layers Description

| Layer | Purpose | Examples of Standards |
| --- | --- | --- |
| Syntactic Interoperability | Understanding of data structure in messages exchanged between systems | IEC Family (61850, 62056, 61970, etc.) |
| Network Interoperability | Exchange messages between systems across different networks | IP Suite |
| Basic Connectivity | Mechanisms to enable physical and logical connectivity between systems | IEEE 802.x Family (802.3, 802.11, 802.16, 802.15.4, etc.) Powerline (HomePlug, Prime, IEEE 1901 Family) |

mains are defined separately. A rank is established wherein standards from European Organizations are considered first; then, if no standards from these institutions are available, ISO, IEC and ITU standards are considered. If still there are no standards to address particular aspects of SGs, then they are considered in an open basis. Communications technologies and standards are addressed considering wired and wireless media, with a particular reference of powerline, and matched with SGAM sub-networks as presented in Table 2.5, adapted from [26]. In term of the last-mile it is noticeable the different networks that are associated with it namely the subscriber access network, neighborhood network and the field area network.

Eurelectric and the European Distribution System Operators (EDSO) association have jointly defined the priorities in terms of standardization for smart grids. In [27] standards are approached according to three main categories: network management; integration of DG and EV; and market and customers. No recommendation in terms of communications technologies is made by these associations since different applications, scenarios and performance related issues need to be addressed. All technologies should be considered, either wired or wireless. They recognize the convenience of PLC related technologies in ensuring a low invasive connectivity infrastructure, especially in locations without radio coverage, but they also raise concerns associated with electromagnetic interference phenomena. A general recommendation is made about the possibility of using PLC in MV and LV networks along with complementary standards and regulation efforts to address interference. The use of PLC for mission-critical functions is recommended to be further addressed namely at the technology level. In terms of data models several IEC standards are identified considering the data models for electric devices, the structures and semantics of Common Information Model (CIM), Internet based web services, cyber-security, among others.

The International Electrotechnical Commission (IEC) is one of the standardization bodies most committed to developing standards for smart grids. It is well known the extensive work developed by IEC, namely for the electric industry, and a strategy group was recently created with the objective of defining a smart grid standardization roadmap [22]. This document incorporates IEC standards envisaging the enhancement of monitoring and control systems and components of SGs by means of semantic and syntactic interoperability. With this respect, one of the most significant contributions is the Seamless Integration Architecture (SIA) defined by the Technical Committee 57 (TC 57). This interoperability model is part of the IEC 62357-1 standard [28] and is reproduced in Fig. 2.9. It combines IEC standards with application and business layers at the top and middle, electric power systems at the bottom and security and data management in the left [9].

Table 2.5: ESOs Communications Technologies and Standards for SG sub-networks

| **Standard/Technology** | **Subscriber Access Network** | **Neighbourhood Network** | **Field Area** | **Low-end intra substation** | **Intra-substation** | **Inter-substation** | **Intra control centre** | **Intra data centre** | **Enterprise** | **Balancing** | **Interchange** | **Trans regional** | **Trans National** | **WAN** | **Industrial Fieldbus** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Narrowband PLC (LV & MV) | x | x | x | | | | | | | | | | | | |
| Narrowband PLC (HV & VHV) | | | | | x | x | | | | | | | | | |
| Broadband PLC | x | x | | | | | | | | | | | | | |
| EN 14908 | | x | x | | | | | | | | | | | | |
| EN 50090 | | x | x | | | | | | | | | | | | |
| IEEE 802.15.4 | x | x | x | | | | | | | | | | | | |
| IEEE 802.11 | x | x | | x | x | | | | | | | | | | |
| IEEE 802.3/1 | | | | x | x | | x | x | x | | | | | | x |
| IEEE 802.16 | x | x | x | | | | | | | | | | | | |
| ETSI TS 102 887 | | x | x | | | | | | | | | | | | |
| IPv4 | x | x | x | x | x | x | x | x | x | x | x | x | x | x | |
| IPv6 | x | x | x | x | x | x | x | x | x | x | x | x | x | x | |
| RPL/6LowPan | x | x | x | | | | | | | | | | | | |
| IEC 61850 | | x | x | x | x | x | | | | | | | | x | |
| IEC 60870-5 | | | | x | x | x | | | | | | | | x | |
| GSM/GPRS/EDGE | x | x | | | | | | | | | | | | x | |
| 3G/WDCMA/UMTS/HSPA | x | x | | | | | x | x | x | x | x | x | x | x | |
| LTE/LTE-A | x | x | x | x | | x | x | x | x | x | x | x | x | x | |
| SDH/OTN | x | x | x | x | x | x | x | x | x | x | x | x | x | x | |
| IP MPLS/MPLS TP | x | x | x | x | x | x | x | x | x | x | x | x | x | x | |
| EN 13757 | | x | | | | | | | | | | | | | |
| DSL/PON | x | x | | | | x | | | | | | | | x | |
| | **Last-Mile** | | | | | | | | | | | | | | |

Table 2.6 only summarizes the IEC core of SG family standards[3] and respective target applications, given the extensive listing of IEC SG related standards.

### 2.6.6 Technical and Market Operation for EV Integration

The changes introduced by the modernization process of the electric power system will have significant impact on both technical and market operation strategies envisioned within the smart grids concept.

The integration of DERs and flexible load devices is motivating research in both domains. This accounts not only for the electrical changes, like enhanced protection schemes among other challenges

[3] Adapted from IEC website: http://www.iec.ch/smartgrid/standards/

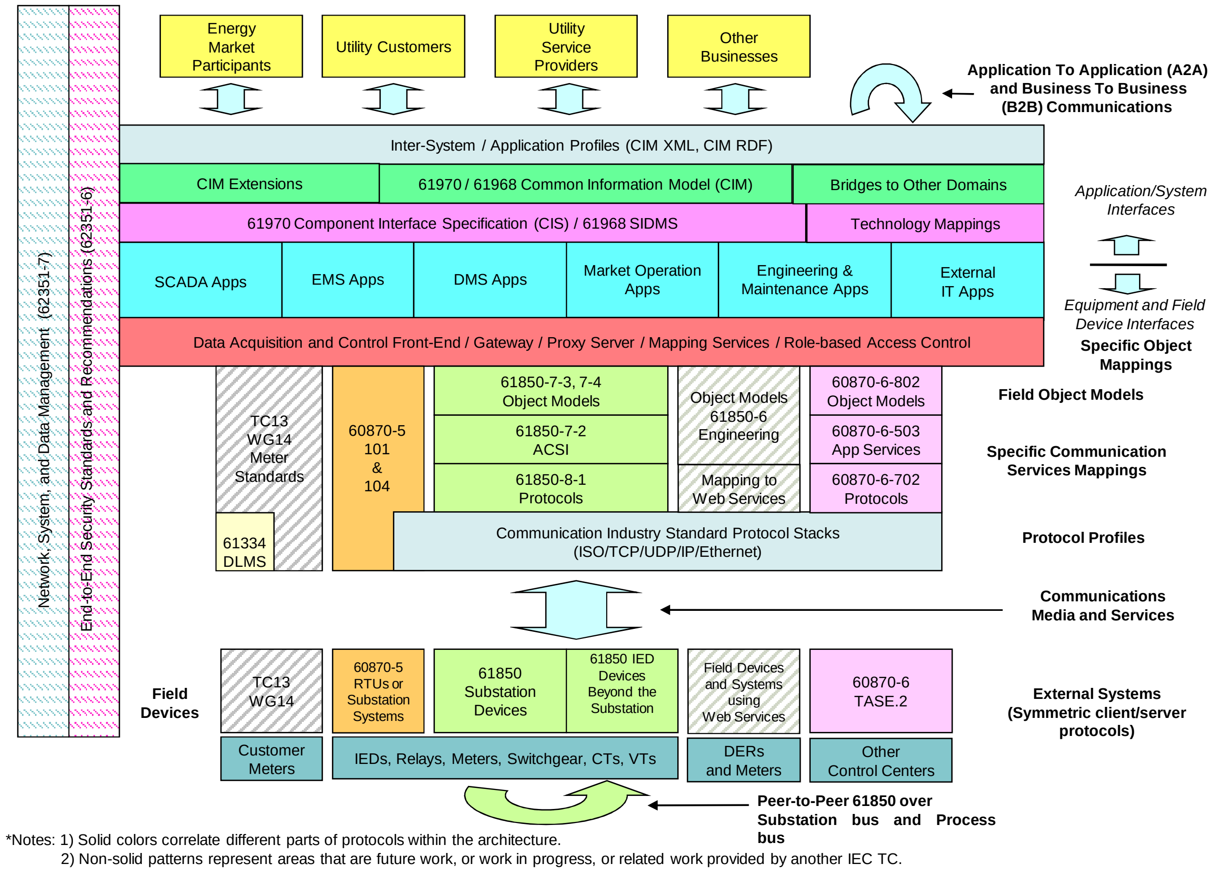



Figure 2.9: IEC TC-57 SIA

identified previously, which must be supported by proper communications solutions, but also the implementation advanced market schemes that enable the integration and active participation of customers in a service exchange perspective.

Hence the importance of considering and defining new participating entities in smart grids, which have been targeted by the research community. One of such example is the EV, which by its nature not only represents a mobile and flexible load but also represents a DER with the ability to inject power into the grid. This has led to the definition of conceptual frameworks to deal with grid technical management and market operation issues raised by the introduction of EVs.

#### 2.6.6.1 Electric Vehicles

The introduction of electric vehicles in distribution grids is being regarded as a challenge but also as an opportunity. The challenges are mainly put at technical and operation levels whereas opportunities are associated with new services to be introduced, benefiting customers, service providers and electric system operators.

Table 2.6: IEC Smart Grid Core Standards

| | |
|---|---|
| **Family:** | IEC/TR 62357: Service Oriented Architecture (SAO) |
| **Applications:** | EMS, DMS |
| **Family:** | IEC 61970: Common Information Model/ Energy Management |
| **Applications:** | EMS, DMS, DA, SA, DER, AMI, DR, Storage |
| **Family:** | IEC 61850: Substation Automation |
| **Applications:** | EMS, DMS, DA, SA, DER, AMI, Storage, EV |
| **Family:** | IEC 61968: Common Information Model (CIM) / Distribution Management |
| **Applications:** | DMS, DER, AMI, DR |
| **Family:** | IEC 62351: Security |
| **Applications:** | EMS, DMS, DA, SA, DER, AMI, DR, Smart Home, Storage, EV |
| **Family:** | IEC 62056: Data exchange for meter reading, tariff and load control |
| **Applications:** | - |
| **Family:** | IEC 61508: Functional safety of electrical/electronic/programmable electronic safety-related systems |
| **Applications:** | - |

#### 2.6.6.2 Participatory Roles

The particular characteristics of EVs allow them to potentially play different roles in the electric grid. In fact, it is expected that in most cases EVs will be parked during longer periods than when moving, which makes them suitable for flexible service exchange. As pointed out in [7] EVs can act as:

- Loads - the recognized flexibility in battery charging allow EVs, while loads, to have different behaviors such as:
  - Uncontrolled - no control over the charging process is exercised and as soon as the EV is connected to the grid and, if needed, it instantaneously starts charging. This means that the charging pattern is entirely controlled by the internal battery management system;
  - Controlled - the charging process is controlled by external parameters often associated with a tariff oriented scheme, where EV owners select the charging period with a favorable economic counterpart, or the customer allows the utility or service provider to control the charging process in light of economic incentives. In the latter case EVs can potentially participate in system services to the grid.
- Power Sources - within the Vehicle-to-Grid (V2G) concept EVs are not only managed as controllable loads but also as storage devices. In case there are economic incentives, it may be possible to ensure their participation as an auxiliary power source, thus providing a form service to the electric grids. Peak shaving, congestion management, voltage control and micro-source operation are within the potential services in which EV can actively participate.
- Ancillary Service Providers - the provision of these services assumes the integration of EVs in the existing system, considering both technical and market operation. This way, EVs are able to provide:
  - Frequency Control:

      * Primary - reacting locally to system frequency disturbance events, through the use of proper controllers, for example based on droop control schemes;
      * Secondary Frequency Control - enabling the market participation through an AGC in the secondary reserve.
  - Voltage Control - as storage devices, EVs have the ability to inject power into the grid and their controllability enables them to potentially participate in voltage regulation and congestion management activities.

#### 2.6.6.3 Charging Strategies

As mentioned before, EVs represent flexible loads over which specific control strategies can be implemented, being one of such cases the charging process. In fact, the control over the EV charging schemes, represents a very desirable feature for the utilities and, given certain economic incentives, for customers too. According to the used power level, the charging process can be divided into slow or fast. Fast charging usually means that the EV is only connected to the electric grid during short periods of time and these services are usually priority, under normal operating conditions any control action will hardly be allowed or even feasible. Hence the interest in exploring slow charging strategies that have potentially higher flexibility in terms of control of the charging process, like those presented in [6]:

- Uncontrolled Charging:
  - Dumb Charging - also known as strictly uncontrolled where no restrictions or incentives are introduce to the charging process, being EVs treated like any regular load that starts charging at a rated power immediately after the grid connection;
  - Multiple Price Tariff - this mode also allows EVs to be charged as soon as they are connected to the grid but an economic incentive, via different tariff prices, is provided to promote the charging process at specific hours of the day and thus modulate the charging process according to the electric power system operation.
- Controlled Charging:
  - Smart Charging - an external control is responsible for the charging process, usually managed through aggregating entities to have impact over the remainder control schemes within the grid operation. This mode is market oriented and, according to the contract established between the EV owner and the market representative, like an electricity retailer, and the market negotiations carried out by the representative, charging set-points are exchanged with the charging infrastructure. This mode relies also on an information exchange process to implement the charging conditions or to change them if there is flexibility for that. This mode can potentially enable the provision of ancillary services by regulating the charging power, for instance to deliver upward or downward reserve services;
  - Vehicle-to-Grid (V2G) - this mode is regarded as an extension to the previous mode where EVs are able to inject power into the grid, hence maximizing their flexibility. Despite the obvious advantages in terms of control there are also battery degradation issues by exposing them to

an increased number of charging and discharging cycles, which will have to be compensated by some type of economic incentives to promote this type of participation.

#### 2.6.6.4 Vehicle-to-Home

One specific application considered for EVs consists in focusing the V2G concept solely on the domestic environment. This concept is often referred to as Vehicle-to-Home (V2H) being the EV the centerpiece element of a domestic energy portfolio. The implementation of V2H strategies depends on the existence of infrastructure devices, which may range from smart meters to expensive grid forming inverters that the integration of EVs along with available microgeneration sources and controllable loads. This requires a communications network, Home Area Network (HAN), that interconnects all elements with the managing entity, usually associated with the smart meter. In a V2H system the user has the opportunity to make an integrated management of the stored energy in the batteries of the EV with the electric consumption of domestic appliances. These managing systems can bring significant benefits to both customers and utilities, since with the proper economic incentives allow the implementation of energy efficiency strategies like load shifting from peak demand periods, thus reducing the expenditures regarding the electric energy consumption [46]. The EV batteries can also be used as an energy backup system within the domestic environment in the event of a power supply shortage or more severe failures.

There are nonetheless some challenges to be addressed in the V2H concept, like the premature wearing down of batteries imposed by this mechanism, which is a concern also associated with V2G. Car manufacturers see the V2H as a potential application associated with EVs, in the sense that customers may take advantage of an emergency backup system within their premises and as such keep the number of charging and discharging cycles within acceptable values. However, there are some concerns towards the feasibility of implementing these strategies while the electric mobility main challenges are not completely solved and subjected to a set of well-defined rules supported by proper standardization [47].

In the MERGE project [48] the V2H concept was addressed with the definition of different use cases according to the available energy portfolio and appliances, considering the isolated and interconnected modes of operation with the electric grid.

#### 2.6.6.5 Integrated Operation

Given the expected growing interaction between market oriented and technical operation entities an integrated vision considering both domains can be considered. In [49] a grid control architecture and a market framework considering EV integration is proposed. Given the potential influence that EVs can have, a specific market entity is considered, designated EV Aggregator, with the main purpose of grouping EVs customers according to their usage profile and willingness in participating in electricity market service exchange. It is assumed that when operating in normal conditions there is a market oriented prevalence that defines the technical operation, in particular assuring the charging process of EVs, after previous validation from system operators. When the electric system operation is compromised, leading to an emergency state of operation, the market orientated operations are suspended, and a technical operation control hierarchy is activated based on the control architecture concepts defined for MGs and MMGs. The overall framework is depicted in Fig. 2.10, which was adapted from [49].

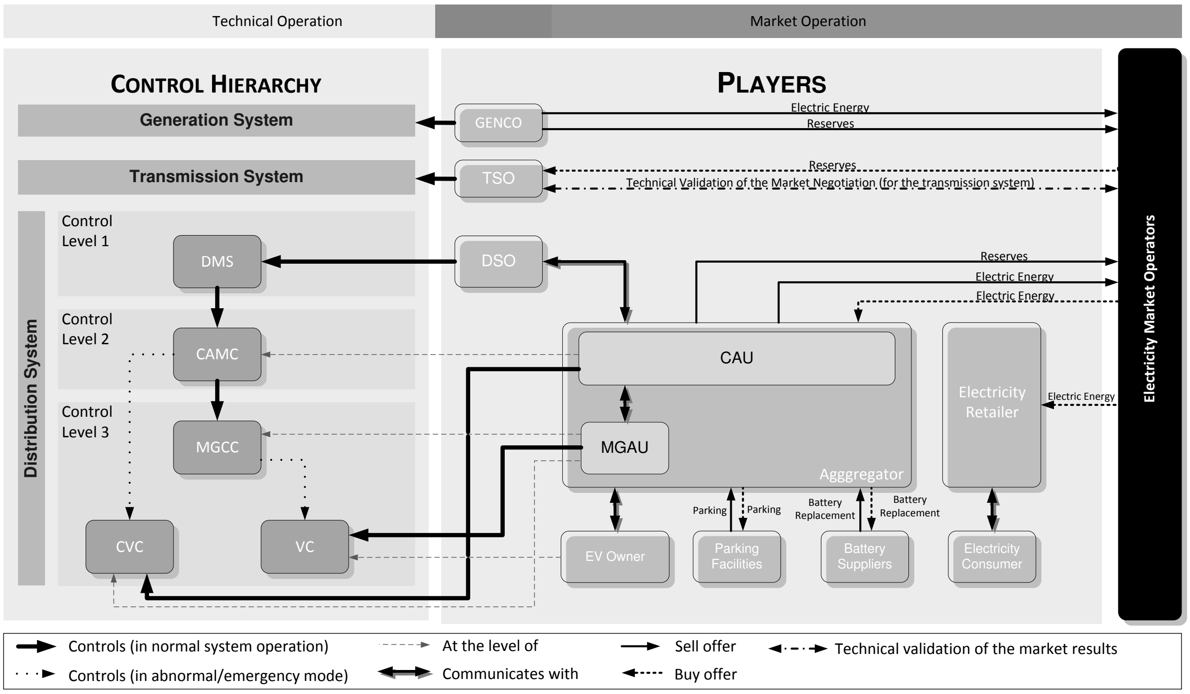



Figure 2.10: Integrated Conceptual Framework

A local controller is defined specifically for EVs consisting of an interface unit with bidirectional communication capabilities which is able to exchange information with a management entity like the aggregator in the market domain or with the upstream control entity (MGCC or CAMC). This controller is designated Vehicle Controller (VC) for single EV or Cluster of Vehicles Controller (CVC) for sets of EVs. The first type concerns typically LV customers individually whereas the latter controls groups of EVs which are fed directly from the MV distribution network.

The conceptual framework illustrated the different interactions that are established when the electric system is operating in normal and emergency conditions. As the data flows are different for both cases, so will the communications requirements due to the expected time horizon of the respective control actions. This emphasizes the importance of architectural models prepared to support such advanced control and operation schemes.

## 2.7 Architectural Models

The evolution of the electric grid is set to introduce the need for new architectures and different concepts to be considered like those presented so far. The main differences in the models considered in this section is mainly due to the different moments in which they were proposed and the intended scope. The models presented in this section have an underlying evolution perspective and as such some share similar concepts and assumptions towards the implementation of solutions designed to support the smart grid.

### 2.7.1 AMI

Smart metering currently represents one of the applications under the smart grid umbrella. The concept was initially developed to allow utilities to remotely collect metering information and nowadays is seen as an opportunity to ensure a dynamic interaction with electricity customers, namely through price oriented service discrimination and other emerging services.

The first concept related with smart metering was the so-called Automatic Meter Reading (AMR), which essentially focused on implementing automated mechanisms for remotely collecting information of electricity consumption from the customer meter [50]. For this purpose IEEE approved the IEEE 1377 standard, which defines a table structure for utility application data to be exchanged with end devices, although no design device criteria or specific protocols are defined to transport that information [51].

An evolution of this model was the Advanced Metering Infrastructure (AMI) concept that introduced a more advanced system composed of metering, analysis, load management modules and a bidirectional communications system. Alongside with AMI, new concepts were defined, such as AMI head-end, which is typically located at the control and operation system of the DSO, and the Smart Meter (SM), which is installed in customer premises. An Automated Meter Management (AMM) layer was incorporated in SMs as a basis to provide services for the customer.

The communications infrastructure associated with smart metering may consist of several networks, typically including a network of meters, a Wide Area Network (WAN) and backhaul networks for the connection of metering networks with a central control operation system of utilities.

The AMI concept was the cradle for the deployment of a communications and processing infrastructure capable of introducing services to the electric network within the smart grid vision. The definition of a smart grid itself is not consensual, either because of different functional model perspectives or due to specific implementation aspects. However, it is widely agreed that it is a complex system composed of interrelated systems that include an AMI or similar smart metering system.

Despite the fact that the first implementations of SGs are majorly based on a sophisticated AMI, there is a concern that this approach may limit or introduce restrictions to the broader objective of progressively creating an integrated bidirectional communications system that also suits more demanding applications. The design of the communications system for a smart grid must take into account the expected long term requirements, even if in the short term only a limited set of functions is necessary (e.g., monitoring or metering). Therefore, a proper communications infrastructure needs not only to account for smart metering existing services but consider also future services requirements that SM will support, like ones being considered for the electric mobility applications, which include among others, enhanced tariff scheme integration for customer EV charging strategies and grid service provision [52].

### 2.7.2 NIST

The National Institute for Standards and Technology (NIST) has recently developed reference models according to a detailed vision of challenges and issues of communications within smart grids. The model proposes a separation of the global SG concept into network segments considering a logical separation based on functional aspects. It incorporates the requirements identified by different entities such as governmental, standardization bodies, utilities, electric network operators, suppliers, manufacturers and other stakeholders.

In this context, NIST has defined the key players envisaged for smart grids. They were identified in a domain perspective within which internal elements are functionally and physically interconnected. The interaction between actors and respective domains are represented in Fig. 2.11 with the lines in full representing the physical connections (electric) and the dashed lines representing the functional connections (data).

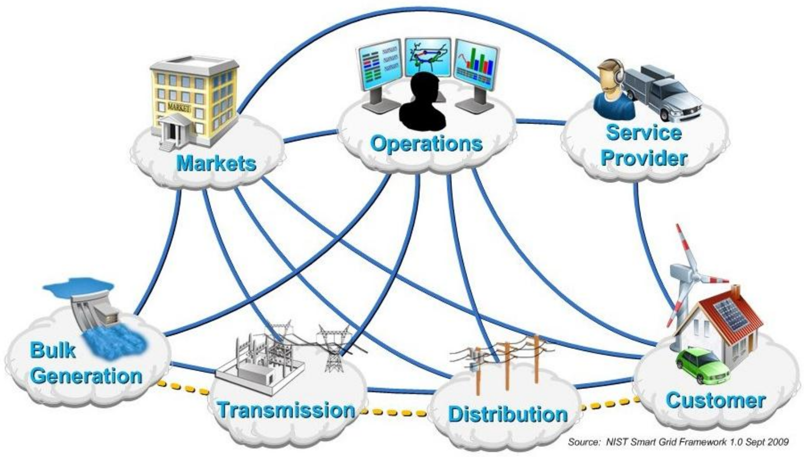



Figure 2.11: NIST Smart Grid Domains Interactions

In [53] a conceptual reference model is established based on a high level perspective with the definition of the main actors and roles in each domain and respective sub-domains. The diagram reproduced in Fig. 2.12, from the NIST framework document, depicts the information exchange that is expected to be established among actors and domains considering different use-cases. The dashed lines represent logic connections or information paths between intra-domain components, whereas lines in full represent inter-domain connections. Information networks are defined as computers or other communication devices that allow the information exchange including the technologies and resource to that end.

Domains are defined as high level aggregating organizations, buildings, individuals, devices or other actors that share similar purposes and objectives. Actors are devices, computation systems, software, individuals or organizations that participate in smart grids and have the ability to make decisions and exchange information with other actors. Gateway actors interact with actors from different domains through information networks. The domains are divided into:

- Markets - operators and other participants authorized to take part in electric energy markets;
- Operations - entities related with system operation;
- Service Provider - entities providing services both to customers and the electric grid in a commercial perspective;
- Bulk Generation - Large and typically centralized electric energy generators;

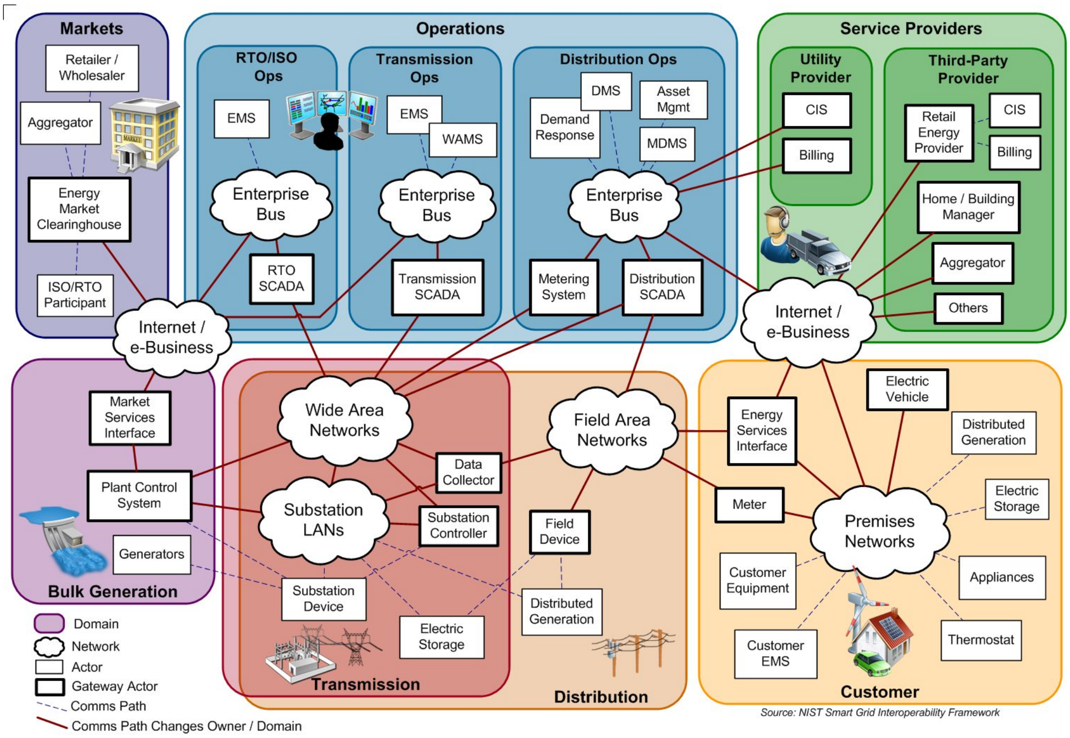



Figure 2.12: NIST Smart Grid Interoperability Framework

- Transmission - entities responsible for the transmission of electricity over large distances;
- Distribution - typically electric energy utilities, which are the final connection link with the end customer;
- Customer - final commercial, industrial or domestic users of electricity that can also store and manage the use of their own energy and can have the ability to inject power into the grid.

A detailed description of the interconnections between the domains and respective actors is presented in [54]. For that purpose the following key use-cases were considered for a generalized SG implementation:

- Wide Area Situational Awareness - involving large electric monitoring systems;
- Electric storage - the use of battery related systems for electric energy storage that can be managed either individually or in an aggregate way;
- Electric transportation - integration of EVs as a load element, potentially flexible, since it can store energy and has the ability to inject power to the grid;
- AMI - advanced metering system that enables bidirectional exchange of information between the customer and the grid or service provider;
- Distribution grid management - management and control of the distribution grid considering the participating entities in previous use-cases.

### 2.7.3 IEEE

The IEEE has defined a Smart Grid Interoperability Reference Model (SGIRM) within the scope of the IEEE 2030 standard [55]. The SGIRM is supported by an end-to-end smart grid communications model, presented in Fig. 2.13, which defines three complementary Interoperability Architectural Perspectives (IAP):

- Power Systems (PS-IAP) - highlights the aspects of production, delivery and consumption of electric energy. It defines logical information to be exchanged;
- Communications Technologies (CT-IAP) - highlights the connectivity aspects among systems, devices and applications. It defines the general communications options for different interfaces and segments;
- Information Technology (IT-IAP) - highlights process control aspects and identifies data flow management aspects.

These IAPs can be further expanded as layers that address specific aspects of the smart grid power, communications and information components.

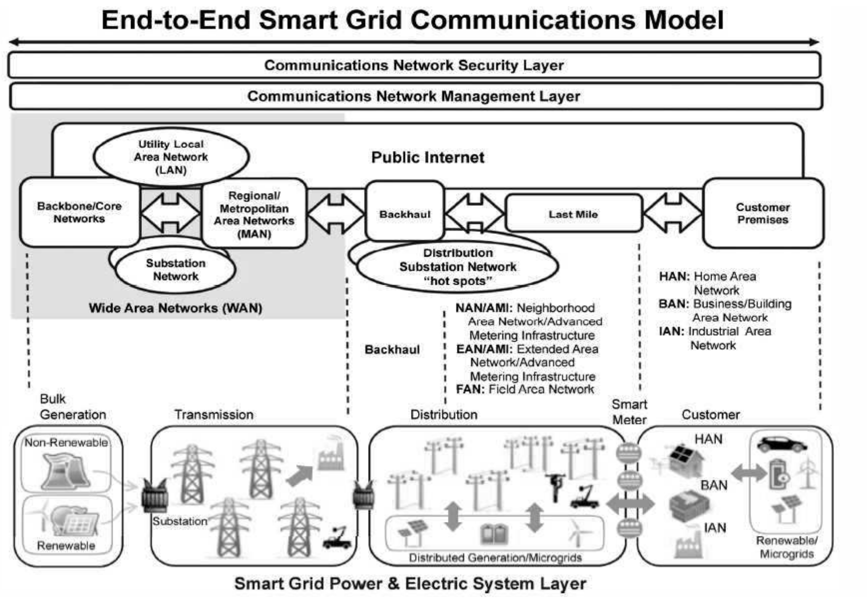



Figure 2.13: IEEE Smart Grid Communications Model

The designations adopted by SGIRM are similar to those of the NIST conceptual model. The overall model is composed of domains, entities and data flows:

- Domains - common to all perspectives, they are divided into: Bulk Generation, Transmission, Distribution, Service Providers, Markets, Control/Operation and Customer;

- Entities - unique to each perspective, they are composed of devices, communications networks, hardware, software and others, located inside a specific domain connected to other entities through one or more interfaces;
- Interfaces - logical connections to support data flows among entities;
- Data flows - application related data exchange sets to provide data to entities.

The PS-IAP represents a layer concerning the domains typically found in electric power systems like generation, transmission and distribution but it considers also the remainder defined in the NIST model. These domains divide the electric power system into a structure, where new functionalities are expected to be deployed. Entities are defined as equipment or functions related with the power system, whereas interfaces are logical connection points between entities that can represent different data flows. Power flows are not considered due to the large number of possible scenarios to account for.

In Fig. 2.13 it is possible to identify some of the earlier mentioned domains and the definition of the communications network segments, separated logically and functionally based on the CT-IAP defined in the standard. The customer premises networks can have different sizes and can be divided into Home Area Network (HAN), Business Area Network (BAN) or Industrial Area Network (IAN) depending on the type of customer. The distribution substation networks can be classified according to different functionalities into Neighborhood Area Network (NAN), Extended Area Network (EAN), Field Area Network (FAN) or Advanced Metering Infrastructure, the latter as a legacy designation. Substation networks are defined as Wide Area Networks (WAN), as they represent the data networks with broader range. This communications layer associated with the CT-IAP also considers the transverse use of public Internet based networks over the four domains. It is presented as an alternative, since utilities and other stakeholders may be reluctant to such solutions where communications networks might not be owned by them. The need for communications network management and security is emphasized also as a transverse theme.

The CT-IAP, represented in Fig. 2.14, considers multiple communication networks that are envisaged by IEEE to be established over different segments of smart grids. On one hand it is considered that some of these networks can be well delimited and directly overlaid into specific electric network segments to interconnect devices in a well-defined area. On the other hand different networks may be considered according to different abstractions of possible interconnections, which may include and span over several segments. These networks can include common entities but they are differentiated by the scope, functionality or geographic area.

An overall perspective of the communications networks referred in CT-IAP is shown in Fig. 2.15 to easily identify the scope of each one and the involved entities and devices. As pointed out in the IEEE 2030 standard, the communications perspective is technology and protocol agnostic, thus enabling a standard-based interoperability approach. It is emphasized that the multi-network and multi-technology nature of SGs will have to support different types of applications, like the cases of smart metering and enhanced control and thus support data information exchange schemes with quite different requirements.

The IT-IAP represents the perspective of data flows associated with IT applications used to manage and operate the electric power system providing an upper layer of abstraction that allows interoperability and independence of different systems. The defined entities represent aggregations of databases and

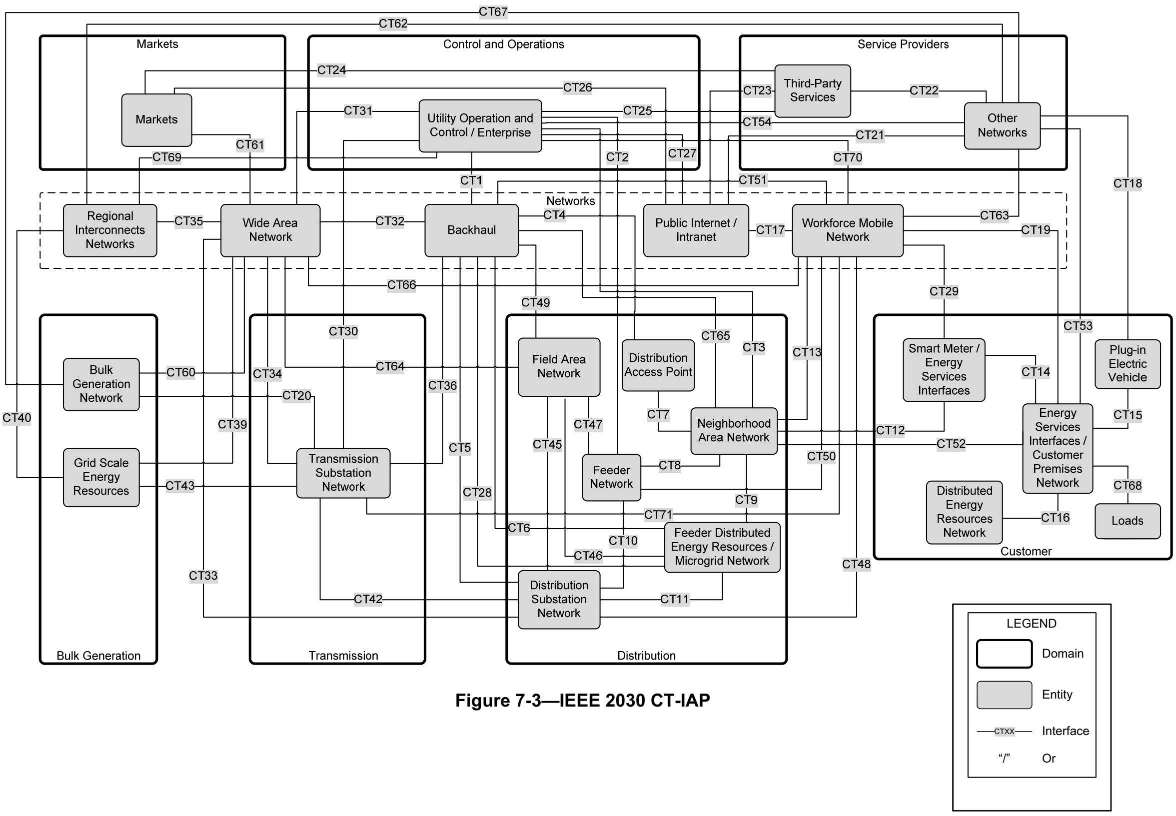



Figure 2.14: IEEE 2030 CT-IAP

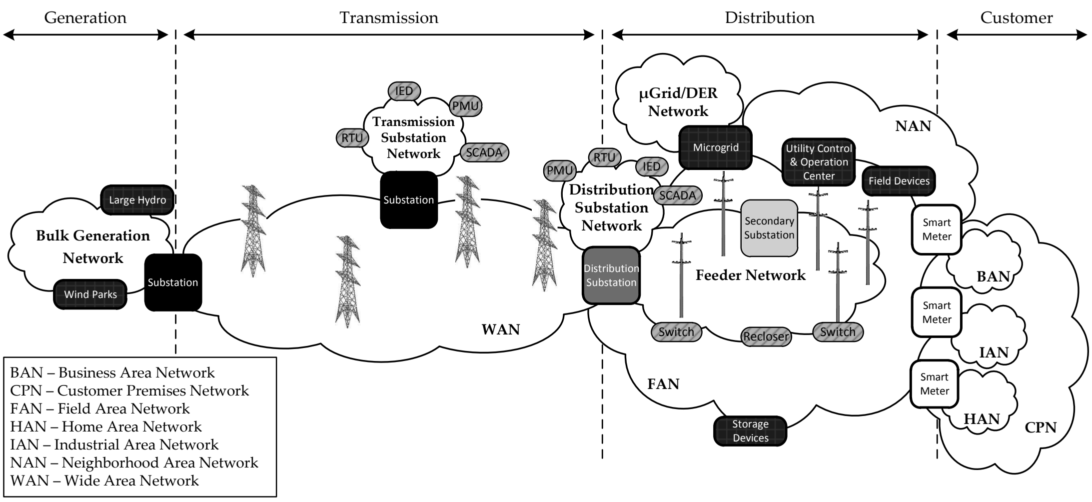



Figure 2.15: IEEE 2030 Network Interconnection of CT-IAP

protocols. Data flows are defined along with information exchange mechanisms at the application level, considering the different domains and segments previously mentioned.

### 2.7.4 SGAM

The European Standards Organizations (ESO) have released in late 2012 a set of documents within their participation in the EU smart grids task force. Among them is a first set of standards documents mentioned in the previous chapter as well as a smart grid reference architecture. This Smart Grid Architecture Model (SGAM) intends to define a European architectural model to represent the smart grid as set of abstract domains incorporating all the major stakeholders. It intends to provide a methodology applicable to a large number of use cases as a guide to potential stakeholders focusing on implementation aspects and allowing the identification of standardization gaps [56]. The elements of SGAM can be divided into: a conceptual model; a framework; and the different architecture elements.

The definition of a conceptual model was considered in light of the M/490 mandate which defined the basic principles for smart grid related models in Europe. The concept model builds on the one defined by NIST, where DERs are also considered at the domain level since they represent a particular type of generation typically connected to distribution networks (LV and MV) and are one of the vectors of the energy decentralization paradigm fostered by the smart grid concept. Fig. 2.16 from [56] illustrates the introduction of the DER domain along with the interactions with the distribution domain. One interesting fact is the representation of the microgrid concept within the extended model, which includes three domains and the definition of the transmission and distribution domains as a pan European energy exchange system. The conceptual model is portrayed as a future-oriented model allowing centralized, decentralized or mixed approaches.

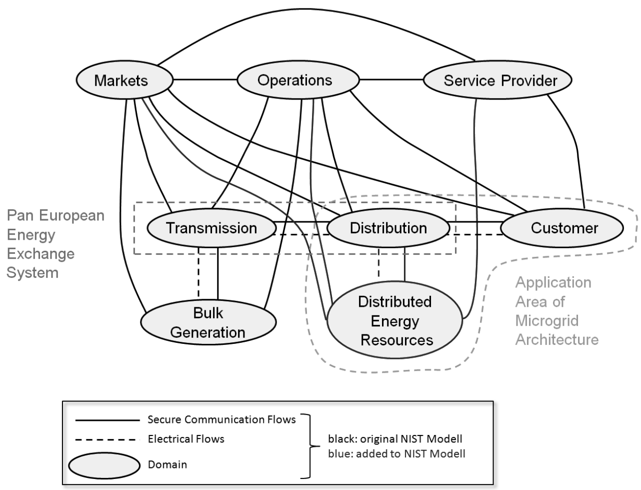



Figure 2.16: SGAM Concept Model Extension

Based on the well-established GWAC interoperability categories, a reference architecture framework, presented in Fig. 2.17, was defined. According to [56], the following layers were established:

- Business - addresses regulatory and economic structures, policies and business models as well as the definition of new market oriented models;

- Function - tackles the functions and services independently from systems, components or other the physical implementations, where use cases provide a major contribution;

- Information - concerns the exchanged information between functions, services and components, considering canonical data models as the common semantics for interoperability;

- Communication - involves the protocols and mechanisms to ensure the information exchange between different components according to use cases, functions, services or data models;

- Component - includes actors, applications, equipment, devices, communication infrastructure components and other computerized elements.

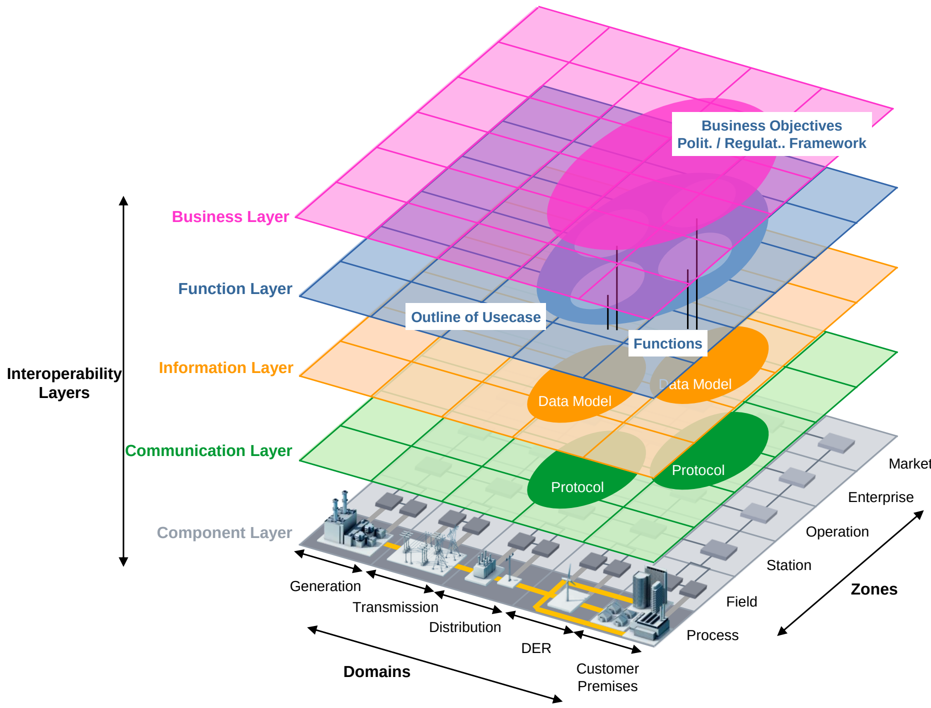



Figure 2.17: SGAM Reference Architecture Framework

SGAM also addresses all of the architecture elements associated with each layer. On one hand, within the information layer, it can be highlighted the definition of data models and interfaces that allow different information flow to be established. On the other hand it is also worth mentioning the communications architecture within the corresponding layer, where different communication network segments are established, considering the aforementioned domains of the conceptual model, along with several recommendations related with interoperability and standardized approaches.

### 2.7.5 Logical and Physical Segmentation of Communications Networks

These different architectural models consider different network segments within the scope of smart grids. A possible criterion for segmentation can be based on functional areas of the electric power system namely generation, transmission, distribution and end customer.

Hence, a WAN can be defined as a network that integrates entities participating in the transmission and bulk generation segments, including substations and transmission operation and management elements. Similarly a FAN can be conceived for the aggregation of entities participating in the distribution segment, including HV/MV substations, MV/LV secondary substations and end-customers. A LAN, typically an in-building network, is constituted of devices within the customer premises. The premises networks, as defined by IEEE, are typically HANs, IANs or BANs depending on the type of customer.

A common aggregation of the segment below the MV/LV secondary substation and the customer premise network can also be considered. This is often designated as the last-mile network, depicted in Fig. 2.18, where a potential large number of nodes exchanging information can lead to dense networks (e.g., hundreds of smart meters per LV feeder). The geographic span of this segment is often identified as being typically within a few km, which justifies the designation of last-mile.

Other criteria may justify different network segregation models, like geographical, administrative, physical and logical reasons that have a significant impact on technology selection and implementation of specific solutions. It is usually considered the need for back-haul networks that bridge the gap between last-mile access networks and WANs. However, the boundaries between such networks are not always clear since in some cases they may share a common infrastructure and inter-working systems. The latter may operate at different protocol layers, acting as repeaters, data concentrators, routers or even application gateways.

In access or last-mile segments the distinction between communications networks may be defined by the types of interconnected devices or by the supported application. This distinction may be physical, when separate infrastructures, possibly of different technologies, are used; or logical, over a shared infrastructure. In the next chapter the discrimination over network segments considering physical and logical separation is approached.

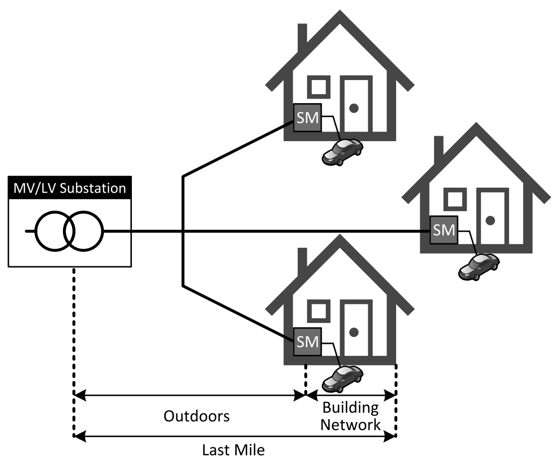



Figure 2.18: Last-Mile Segment

## 2.8 Communications Technologies

There are a wide variety of communication solutions envisaged for smart grids, according to the target applications and, more importantly, to the specific vision of what a SG should be. Economic factors along with technical limitation aspects are also among the reasons for electing particular technologies in detriment of others. The technologies targeted for the distribution segment of smart grids can be classified along two perspectives: on one hand the use of public or private networks and on the other hand the use of wired or wireless technologies.

The use of communications services provided by telecommunication operators using their infrastructure, for instance based on copper, fiber optics, or cellular networks, is regarded by utilities with some skepticism. In these cases they have limited control over the provided service, which may not guarantee the security, availability and reliability indices usually associated with the electric sector. Performance is also regarded as a matter of concern especially when critical real-time applications are considered. However, the use of these networks is considered acceptable, from the perspective of utilities, for non-critical applications in scenarios where due to technical or economic reasons it is not feasible to deploy private networks. Another scenario considered is the use of public operator based solutions as a backup or redundant communication service.

The deployment of private networks in back-haul or backbone segments by utilities has been a common practice over the past years, using twisted copper, optical fiber or wireless technologies in a point-to-point or multipoint configurations.

For these reasons, the discussion of communications network solutions for the electric grid is mainly focused on private networks, namely in the distribution segment, where different implementations are still being evaluated. This presents several challenges in terms of involved entities and domains and a communications infrastructure to support the envisaged smart grid of the future.

From a technological point of view, the use of wired technologies is somehow narrowed down to the use of the power lines as a communication medium, given the technical and economic constraints of deploying a new cabled communication infrastructure, like copper or optical fiber. Hence the use of wired technologies other than power line seems to be unfeasible, at least in the short to medium term, and wireless solutions can be considered as a feasible alternative or even as complementary system.

### 2.8.1 Power Line Technologies

Power Line Communications (PLC) technologies explore the use of electric power lines (LV, MV or even HV) as a medium that enables the bidirectional data exchange. They have been used for decades in the utility industry for remote metering and load control applications [57]. In recent years, smart grid activities and advances in building and home automation have brought a lot of attention to PLC technologies as an alternative to unwanted or impractical wiring to setup a communications network.

From a technological point of view PLC implementations can be divided into narrow and broadband and they typically target different network segments within smart grids. The narrowband uses transmission frequencies up to a few hundreds of kHz (e.g., 3~500 kHz) whereas broadband operates in the MHz band (e.g., 2~30 MHz or higher).

However the objective might not always be a matter of applying advanced modulation and/or different coding techniques to achieve higher data rates. Power lines are inherently exposed to time-frequency varying noise, unmatched loads and interference from electrical or communications devices. The fact that in electric distribution networks the power lines can vary from grounded to overhead lines introduces even further challenges in using this type of medium to propagate data. On the other hand national legislation limits the transmission power and accepted frequency bands. For these reasons a large number of PLC technologies have been developed each one addressing different applications and thus targeting different throughput values, frequency bands and channel access mechanisms. The implementations of PLC are supported by standards that range from open to proprietary, including some cross solutions.

In the narrowband version, PLC is already used in some applications for power systems to ensure connectivity and data exchange within the electric grid. The technology has also been used in domestic environments in home automation applications or as support for general purpose LANs. This narrowband technology offers modest data rates, up to a few dozen kbps, and it is considered mainly for smart metering applications. However, the adverse characteristics of the PLC medium may introduce severe limitations even for simple applications, particularly in dense urban areas with hundreds of potential communicating nodes attached to the same communication channel.

The recently approved Broadband PLC (BPL) standards promise high throughput in the order of tens or even hundreds of Mbps and enhanced control and coding mechanisms are potential candidates to be considered and evaluated for the electric grids, as the technology becomes increasingly mature.

Given the difficulties conveying data in PLC network, wireless technologies have started to emerge as feasible alternatives, which is reflected in a number of initiatives led by standardization bodies, utilities and manufacturers, along with demonstration projects and pilot trials in electric grids. Nonetheless, wireless solutions present themselves their own challenges, but the ability to extend the coverage area of a communications infrastructure is one of the main attributes to be explored within smart grid scenarios. Besides, PLC technologies are becoming more advanced and promise to deliver data rates up to 1Gbps [58].

#### 2.8.1.1 Narrowband PLC

Narrowband PLC (NB-PLC) currently includes two versions: low and high speed. Narrowband high speed is also sometimes referred to as medium speed, to distinguish from "true" high speed data rate usually associated with the BPL definition. Besides the allowed frequency ranges, there is also a maximum allowable transmission power in each range that must be respected, according to the legal dispositions of each country. The development and dissemination of NB-PLC is promoted by Standard Development Organizations (SDO) as well as by non-SDO consortia. The narrowband region can be further divided into legally allowed frequency bands depending on specific continent or country definitions:

- In Europe CENELEC has standardized and authorized the use and range of frequency bands between 3 to 148.5 kHz, as described in EN50065-1. Bands are further subdivided into what is generally known as "CENELEC bands"[2]:
  - Band A: 3-95 kHz. Only utilities are allowed to use this band;

[2]The total frequency range of 3 and 148.5 kHz is available for utilities whereas for end-user applications the 95 to 148.5 kHz is available

  - Band B: 95-125 kHz. All may use this band.
  - Band C: 125-140 kHz. All may use this band when using CSMA;
  - Band D: 140-148.5 kHz. All may use this band.

- In USA, the FCC has established the use of band ranges from 10 to 490 kHz;
- In Japan, the ARIB defined band ranges from 10 to 450 kHz [59].

The first generation of NB-PLC made use of single or double carrier transmission schemes with simple modulation schemes such as Phase Shift Keying (PSK) and Frequency Shift Keying (FSK) to achieve a few kbps usually targeting remote metering applications.

Two non-SDO second generation NB-PLC technologies are G3 and PRIME, which were developed having in mind smart metering communications scenarios. Both use an Orthogonal Frequency Division Multiplexing (OFDM) modulation technique, but subtle physical layer details make the two technologies differ a little [60]. As a general rule, PRIME achieves higher data rates while G3 has a more powerful error correcting algorithm in order to achieve improved reliability [60]. At higher layers the two technologies are similar. The maximum data rates within CENELEC band A are 33 kbps for G3 and 128 kbps in the PRIME case. The G3 standard is maintained by the G3-PLC[3] Alliance while PRIME is maintained by the PRIME Alliance[4]; both are available as open industry-standards.

Despite the initial motivation of G3 and PRIME, EV communications is also considered as a potential application to be supported by these technologies. In fact, one of the main advantages of narrowband PLC communications is the possibility of dedicated utility frequency band. For this reason companies have implemented point-to-point variants of G3 and PRIME, which are designed for the communication between two nodes, as in the case of EV and the EVSE charging infrastructure and the EVSE and the distribution grid. In the G3 case, it is possible to extend beyond the CENELEC A band to achieve higher data rates.

Since neither G3 nor PRIME were specifically developed for EV communications and the fact that they represent non-SDO standardized implementations, several communications technologies are considered for ISO/IEC 15118-3, which include G3, PRIME and other solutions rendering some uncertainty towards the PLC variant used in EV applications [22].

The International Telecommunication Union (ITU) defined G.hnem project to address home networking for energy management using high speed OFDM NB-PLC. One objective of the ITU Telecommunication Sector (ITU-T) in this project was the development of a unified next generation narrowband PLC. It integrates some of the features present in G3 and PRIME, which were complemented with coherent reception, enhanced protection against power line impulsive noise, multiple bands for worldwide compatibility, adaptive medium access rules and support for multiple network protocols [61]. Within this project scope, ITU-T targeted at applications such as AMI (residential or business) and EV charging. Recommendations G.9955 and G.9956 are part of G.hnem and define respectively the physical and data link layers. The physical layer uses CENELEC and FCC bands with up to 16-QAM subcarrier modulation with data rates up to 1 Mbps. Forward error correction schemes are used to improve robustness against

[3] "G3-PLC Alliance" - http://www.g3-plc.com/
[4] "PoweRline Intelligent Metering Evolution" - http://www.prime-alliance.org/

noise. The defined medium access method is a prioritized CSMA/CA. Automotive support is provided allowing operation over main and pilot wires [62].

An emergent standard for narrowband PLC is P1901.2, which is being developed by IEEE since 2009[5]. Defined as a low frequency OFDM-based narrowband power line standard for smart grid applications, it is set to use frequencies below 500 kHz and data rates up to 500 kbps, supporting both indoor and outdoor communications. In the outdoors context this standard targets the use of MV and LV electric distribution networks for both urban and long-distance rural feeders. It defines a communications medium for WAN and FAN segments, ensuring connectivity between the electric grid and the customer, through the smart meter. In indoors environments the standard is regarded as an alternative for HAN implementations. The potential applications targeted by P1901.2 are grid to utility metering devices communications, EV to charging station, and HAN related communications aspects, along with other candidate applications. One particular aspect of this standard seems to be the coexistence philosophy, as defined by NIST PAP 15, which is being adopted by IEEE. It aims at providing the required mechanisms to allow this technology to coexist with PRIME and G3, somewhat similar to the earlier described approach of ITU-T regarding G.hnem (G.9955 and G.9956).

#### 2.8.1.2 Broadband PLC

The cradle of broadband PLC was the domestic environment as a technological alternative to enable Internet services to end users through existing power lines at home. This should not be confused with the provision of Internet services using PLC in the last-mile access network, as an alternative to copper (e.g., DSL) or optical fiber. Although it is often associated with a replacement to in-building Ethernet networks, the use of BPL has been implemented using different technologies and approaches. Recently it has been considered as another candidate for communications outside the building environment, namely for the last-mile segment.

Wide frequency bands, typically between 2~30MHz, are generally available worldwide for all purposes, except in Japan, where it is not allowed to use PLC in this frequency range. Technically, the upper limit to wide band communications in power lines is dictated by the minimum communication distance and the use of TV broadcast signals above 80 MHz. Some wide band solutions use a frequency range up to 60 MHz. Evidently, a wider band allows a higher number of OFDM subcarriers to be used and thus yields higher theoretical data throughput, although this also depends on other factors like the modulation scheme used in each subcarrier. For wideband PLC a high number of subcarriers can be used, depending on the standard, when compared to the narrowband implementation where typically around 36 subcarriers are used in the CENELEC bands [60].

A particular implementation of BPL is HomePlug, which was designed for the domestic environment. It was developed by a non-SDO industrial consortia, the HomePlug Alliance, which is responsible for the development of MAC and PHY layers and of different standard versions. In 2001 HomePlug 1.0 was made available using Differential Binary Phase Shift Keying (DBPSK) and Differential Quadrature Phase Shift Keying (DQPSK) modulations and Forward Error Correction (FEC) mechanisms to achieve data rates near 14 Mbps [63]. The variant HomePlug AV, released in 2005 and aiming at high quality multi-stream data over power lines, uses flexible modulation schemes from BPSK to 1024-QAM [64].

[5] "IEEE P1901.2" http://standards.ieee.org/develop/project/1901.2.html

Using FEC schemes along with Robust OFDM (ROBO) or adaptive bit loading techniques, it enables data rates ranging from 10 Mbps up to 200 Mbps at the physical layer. HomePlug Green PHY (GP) released in 2010, is the most recent variant for in-home smart grid and smart energy applications [65]. The HomePlug GP is basically a scaled down version of the HomePlug AV within the context of domestic SG communications where a high data throughput is not the main objective. Instead it focuses on ensuring reliable communications, with good coverage. Hence, HomePlug GP does not support adaptive bit loading using only QPSK as ROBO modulation scheme to ensure high reliability, whilst achieving 10 Mbps [60]. The simplifications introduced in GP makes it lightweight in terms of processing, memory and power consumption requirements, when compared to other HomePlug variants.

Given that GP and AV versions of HomePlug use the same frequency band, they will have to share the available time-on-wire. The CSMA scheme is used in both and given the adverse effect in the medium access conflict resolution, only 7% of time-on-wire is allowed to HomePlug GP devices to ensure inter-operable scenarios. This allows smart grid oriented applications to use the GP version within an already deployed customer HAN based on HomePlug. The EV is considered by HomePlug manufacturers as an important entity to incorporate in domestic networks, namely those based on PLC technologies, with the GP variant targeting also EV communications.

An SDO-based implementation of BPL can be found on IEEE 1901 standard, which defines the MAC and PHY layers for high-speed communications over power lines with date rates up to hundreds of Mbps. The standard defines two MAC layers, targeting separately in-home and access networks (over LV and MV distribution lines) with different requirements and potential applications [66]. It also defines two possible implementations of the PHY layer distinguished by the used modulation scheme: one based on FFT OFDM (FFT-PHY) and another based on Wavelet OFDM (Wavelet-PHY). These two implementations are not compatible and manufacturers can implement only one of them or both. The FFT-PHY can use up to 1974 carriers from 1.8 to 50 MHz with different subcarrier modulation ranging from BPSK up to the optional 4096-QAM. The wavelet-PHY uses 512 subcarriers between 1.8 and 28 MHz using M-PAM modulation schemes, up to 32-PAM. Robust signaling schemes and FEC mechanisms are used to ensure resilience over the transmission medium [67]. Some of the approaches used in IEEE 1901 are expected to be adopted in the future narrowband version, the IEEE 1901.2.

In 2010, ITU-T has also defined a broadband PLC standard for home networking, designated G.hn, with the purpose of supporting smart grid applications such as AMI and energy management including EV. It was designed to be used for robust in-home or last-mile communications, comprising the definition of a physical layer, in G.9960, and data link layer, in G.9961. At the PHY layer an OFDM implementation is defined to be used in two frequency bands. The first band ranges from 2 to 100 MHz allowing up to 1 Gbps data rate. The second band is defined between 2 and 25 MHz and uses a low complexity profile enabling a data rate between 5 and 50 Mbps. The standard defines robust transmission schemes, FEC and repetition encoding to tackle the power line communications medium [68].

### 2.8.2 Wireless Technologies

There is a set of wireless technologies that can be exploited within smart grids, with specific advantages but also some limitations, when used in the last-mile communications network segment, where devices such as sensors and controllers are deployed in critical points of the electric grid. Among these devices are smart meters, concentrators or traffic aggregators in transmission and distribution networks, which can use either wired and wireless solutions to convey data.

There are some advantages in considering wireless communications for the distribution segment such as ease of installation, maintenance and future expansion, allowing a greater degree of flexibility, which may represent a significant leverage when different requirements may exist in current or future vision of SGs. Another advantage is related with the potential low cost, especially when mature and well disseminated technologies with massive production are employed, like the case of Wi-Fi. They are also able to support different and less restrictive device locations when compared with wired solutions and they can support node mobility and interoperability mechanisms. The wireless characteristic can allow the operation of the communications network in the event of a disturbance in the electric grid that impairs communications via power lines. This is especially relevant when considering the operation of isolated systems.

The aforementioned advantages can also be seen as a double-edged sword in issues such as location where radio planning is usually involved and node placing strategies may need to be carefully considered due to the limited range characteristic of wireless links. The adverse propagation conditions of the communication medium often lead to higher information losses when compared to guided media, which is aggravated by time-varying conditions of the communication channel. The coverage is dependent on the allowable power emission, the usable spectrum (free or licensed bands) and the presence of obstacles among other factors. The particular shared nature of the medium is often pointed out as the main disadvantage since it is prone to eavesdropping and it is exposed to interference from different wireless communications systems. Despite the beneficial properties of wireless implementations challenges such as performance and security need to be carefully addressed. The associated cost benefit characteristic may not be so advantageous if new solutions have to be designed to be employed within smart grids.

#### 2.8.2.1 IEEE 802.11 / Wi-Fi

One the most well-known IEEE standards is the 802.11 that defines Wireless Local Area Networks (WLAN) with similar services and behavior of wired Ethernet. There are two modes of communication: in the infrastructure mode, stations communicate through an Access Point (AP) typically connected to a backbone network, usually wired; in the ad hoc mode, stations are able to communicate directly with each other without involving other devices, like an AP.

This family of standards defines the physical and medium access control layers. Multiple non-interoperable alternatives are defined for the PHY layer, using either Direct Sequence Spread Spectrum (DSSS) or Orthogonal Frequency Division Multiplexing (OFDM) over the 2.4 and 5 GHz non-licensed Industrial, Scientific and Medical (ISM) radio bands. At MAC layer a CSMA/CA protocol is adopted. The major characteristics of the most relevant 802.11 variants are summarized in Table 2.7.

The IEEE 802.11n introduced improvements at the PHY layer to enable a higher throughput and enhance the network coverage, using Multiple Input Multiple Output () technology. Additional improvements were introduced in terms of cyber-security by the 802.11i, Quality of Service (QoS) in 802.11e, Wireless Mesh Network (WMN) support in 802.11s and vehicular communications by 802.11p.

Table 2.7: IEEE 802.11 Networks Characteristics

| Characteristic | 802.11 Legacy | 802.11a | 802.11b | 802.11g | 802.11n |
|---|---|---|---|---|---|
| **Bandwidth** | 20 MHz | 20 MHz | 20 MHz | 20 MHz | 20/40 MHz |
| **Frequency Band** | 2.4 GHz | 5 GHz | 2.4 GHz | 2.4 GHz | 2.4/5 GHz |
| **Number of Channels** | 3 | 12/13 | 3 | 3 | 20/40 MHz |
| **Modulation** | BPSK, QPSK, DSSS, FHSS | BPSK, QPSK, MQAM, OFDM | BPSK, QPSK, DSSS | BPSK, QPSK, MQAM, OFDM | BPSK, QPSK, MQAM |
| **Max. Data Rate** | 1.2 Mbps | 54 Mbps | 11 Mbps | 54 Mbps | 600 Mbps |
| **Max. Range** | - | 30 m | 75-100 m | 75-100 m | 150-180 m |
| **MAC Protocol** | | | CSMA/CA | | |

Wi-Fi is the commercial designation of the IEEE 802.11 family and it is promoted by the Wi-Fi Alliance[6], which has contributed for the widespread availability and implementation of this technology. It has led to the mass production of devices with the natural competition between manufacturers allowing costs to be reduced and favoring their usage in the deployment of wireless LANs. This has turned it into a ubiquitous technology used as a basic communications infrastructure. Newer applications in SG also consider the use of Wi-Fi as a candidate technology in certain segments, namely in last-mile scenarios. Distribution substation automation and DER monitoring and control LANs can be implemented through Wi-Fi solutions. In fact, some IEC 61850 based applications consider the use of Wi-Fi [69]:

- Enhanced transformer differential protection - the use of spread spectrum radio in protection and control schemes opens the possibility of having wireless solutions for on-line monitoring of equipment such as sensors and actuators;
- Redundant link for distribution automation system - wireless LANs are pointed as an alternative for IEC 61850 protection and control applications in MV substations;
- Communications-aided line protection - using Wi-Fi supporting the interconnection between substations for line differential protection applications. Laboratory experiments using wireless LAN with repeaters for range extension are referred to as a successful validation for this kind of applications;
- Control and monitoring of remote DER - point-to-point systems are considered as an alternative for distribution automation and DER management, especially in rural areas were other technologies are deemed economically impractical.

#### 2.8.2.2 IEEE 802.16 / WiMAX

In 2001, IEEE released a standard for wireless metropolitan area networks. The IEEE 802.16 standard, as it was designated, defines the PHY and MAC layers of the radio interface of combined fixed and

[6] "Wi-Fi Alliance" - http://www.wi-fi.org/

mobile point-to-multipoint broadband wireless access [70]. The PHY layer defines two frequency bands for specific operational environments. The 10 to 66 GHz band targets Line-of-Sight LoS communications; a single carrier modulation is adopted and channel bandwidths are around 25 MHz, enabling raw data rates up to 120 Mbps. Both Frequency Division Duplex (FDD) and Time Division Duplex (TDD) modes are supported. In the frequency bands below 11 GHz, LOS is not required and both non-licensed and licensed bands are available. The 5.8 GHz band is used for fixed communications, where issues such as interference and compatibility and radiated power constraints need to be considered, since this is the preferred scenario. The 3.5 GHz band is used for fixed and mobile communications but it requires licensing, like the bands in the 2.3 and 2.5 GHz, which are used for mobile communications only. In these bands both OFDM and OFDMA respectively for fixed and mobile access, both allowing FDD and TDD duplexing techniques. Available channel bandwidths vary from 10 to 20 MHz and the channel rates depend on such factors as radio technology, duplexing mode, channel bandwidth and distance; nonetheless, 140 Mbps is an achievable upper band value. The 802.16m amendment for Advanced Air Interfaces introduced enhancements at the PHY layer and antenna design, achieving more than the double of the original data rates.

The Worldwide interoperability for Microwave Access (WiMAX) is a designation promoted by the WiMAX Forum[7], which certifies and promotes the compatibility and interoperability of broadband wireless devices based on the IEEE 802.16 standard. Commercially WiMAX is described as an alternative technology to cable and ADSL for the last-mile wireless broadband access. Some of the applications targeted by WiMAX include Internet access, backhaul support, triple play and, recently, smart grids and AMI. In [69] other applications supported by WiMAX are defined within the smart grids concept:

- Wireless automatic meter reading - as an application defined between AMI systems of utilities, which may also interact with communications systems of service providers;
- Real-time pricing - as another application over AMI systems that allows real-time price models based on real-time energy consumption, enabling customer awareness, and provides the exchange of incentive-based services;
- Outage detection and restoration - the geographical coverage of WiMAX solutions allows the establishment of a two-way communication channel to implement fast outage detection and restoration procedures.

#### 2.8.2.3 IEEE 802.15.4 / ZigBee

The IEEE 802.15 family of standards defines the technologies and solutions for Wireless Personal Area Networks (WPAN). They target the consumer market and ease of connectivity for personal and handheld devices. Specifically, the IEEE 802.15.4 standard [71] defines the specification for low-rate low-power and low-complexity and short-rage WPANs, which are networks designed to convey small amounts of information over relatively small distances. These networks are composed of Full-Function Devices (FFD) that may operate as coordinators, which are devices capable of relaying messages and talk to any other device, and Reduced-Function Devices (RFD), which are intended to run simple applications, and

[7] "WiMAX Forum" - http://www.wimaxforum.org/

can only talk to an FFD. The RFDs are usually power constrained devices. The standard defines the PHY and MAC layers functionalities. The MAC layer uses CSMA/CA and the PHY layer uses a DSSS technique combined with different modulation schemes over three different unlicensed ISM frequency bands:

- From 868.0 to 868.6 MHz - in Europe (1 channel with up to 20 kbps in legacy and 100 kbps in the latest version);
- From 902 to 928 MHz - in North America (10 channels with up to 40 kbps and 250 kbps in the latest version);
- From 2.4 to 2.4835 GHz - Global use (16 channels with up to 250 kbps).

Additional PHY variants were introduced using Direct Sequence - Ultra Wide Band and Chirp Spread Spectrum. Available subcarrier modulations schemes include BPSK, ASK and Offset-QPSK (O-QPSK).

One recent variant was introduced by the IEEE 802.15 Task Group 4 along with the concept of Smart metering Utility Network (SUN). According to [72] SUNs are communications networks that provide metering and control capabilities to a utility system, supporting low-power and large scale applications through point-to-point connections. This amendment defines multiple data rates in different frequency bands ensuring the support of IEEE 802.15.4 legacy devices. One of the objectives is to ensure that a SUN is able to support interoperability in multi-regional unlicensed frequency bands considering different scenarios and traffic patterns. Particularly interesting are the outdoors scenarios in which support for utility SG applications for in the last-mile segment is expected [73].

ZigBee specifies a set of higher layer network and application protocols over IEEE 802.15.4. These layers enable functionalities like initialization, device association/disassociation, security management and address management, among others. ZigBee defines three types of devices: PAN Coordinator (FFD), Router (FFD), End Device (RFD). It also defines three different topologies at the network level: star, tree and mesh. The ZigBee Alliance[8] is responsible for the definition of the ZigBee protocol stack and also promotes the use of networks based on this technology. ZigBee targets applications like building automation, embedded sensing, wireless sensor networks, to mention a few. For smart grids the following applications are considered [69]:

- Control of domestic appliances - as a communications infrastructure for HANs, ZigBee allows appliances to communicate with the network coordinator to control the operating state of devices;
- Direct Load Control - ZigBee allows grid interconnecting networks like AMI to interact with the domestic HAN manager and deliver different degrees of load control to a service operator or utility.

## 2.9 Routing Protocols

The communications networks envisaged for SGs include several segments and a variety of technologies to support different applications with requirements that can be very heterogeneous. This creates challenges in routing and forwarding data, which are posed at network level. Although routing protocols are not

[8] "ZigBee Alliance" - http://www.zigbee.org/

directly addressed in this thesis they need to be accounted for, to ensure the necessary interconnection and interoperability of communications networks that are expected to be deployed in the smart grids.

In [74] a survey of the main routing protocols for smart grids is presented considering different communications networks along with the types of application defined by the US DoE, which was already presented in the previous chapter in Table 2.3. Routing protocols for both wireless and wired technologies are considered although in the latter only PLC is approached since, according to the authors, Ethernet and fiber optics do not introduce routing challenges. A particular attention is given to the combination of wired and wireless protocols, which are analyzed as a hybrid implementation. Despite the multitude of communications networks that can be established with the SGs context they are discriminated in three main types: in-building solutions, generically defined as HANs; access networks between the customer premises and the distribution grid, globally defined as NANs; and finally the connection between the grid and system operator core networks, which are defined as WANs. The main challenges in designing routing protocols are identified: node heterogeneity, where several different nodes like computers, routers, switches, smart meters, appliances, EVs, etc., are expected to be interconnected; interoperability, since different networks with different functionalities, devices, technologies and owners are to be globally integrated; node position, due to constraints associated with the geographic characteristic that can vary significantly in different contexts; network dynamics, introduced by different applications where considerable heterogeneous requirements have to be met and due to the environment upon which some communications technologies have to operate; security and privacy, given that communications networks in SGs can be located in open and potential insecure environments making them prone to malicious attacks as such authentication, confidentiality and integrity are among the major requirements to be met; scalability, as the number of nodes in the same type of network can vary significantly in different contexts, e.g. rural and urban, which means that mechanisms like route discovery and maintenance can be significantly affected by the number of nodes.

The authors of [74] highlighted and summarized the main routing protocols for HANs, which is adapted and presented in Table 2.8. In terms of routing protocols for PLC HANs only the narrowband versions are considered since broadband PLC does not need to use routing. The Adaptive Channel State Routing (ASCR) is highlighted since it allows tacking the variation of a PLC network topology to define a suitable path to reliably send data. As for hybrid protocol implementations INSTEON, PLC-ZigBee and IPv6 RF-PLC are analyzed as possible alternatives for HAN implementation. For NANs only WMN and PLC networks are considered. Regarding WMNs routing protocols are considered in terms of reliable, secure and QoS routing, whereas PLC routing protocols are considered only in terms of reliability. On one hand protocols like Routing Protocol for Low Power and Lossy Networks (RPL), IEEE 802.11s and related variants are within the most relevant wireless NANs routing protocols. On the other Powerline Multipath Routing (PMR) and SMR (SMR) are highlighted as a routing protocol suited for PLC. In terms of WANs routing challenges are mainly identified in potential long distance multi-hop wireless deployments which can be addressed form similar strategies used in other network segments. In WANs core and backhaul technologies are used based typically on public networks, like Ethernet/optical fiber for wired networks, and wireless cellular based networks like WiMAX, 4G and UMTS.

In terms of protocols for low-power and lossy networks LOADng is also worth mentioning, which is an alternative to AODV routing protocol used in some of the on-demand implementations of the

Table 2.8: HAN Routing Protocols

| Routing Protocol | Adaptation Layer | Network Layer |
|---|---|---|
| **ZigBee** | n/a | Tree, on-demand mesh and source routing |
| **6*Low*PAN** | layer 2 routing - mesh under | RPL - mesh over |
| **wirelessHART** | n/a | Graph and source routing |
| **Enhanced least-hop first routing** | n/a | Graph and source routing |
| **ISA 100.11a** | n/a | Backbone routing |
| **Disjoint multi path routing** | n/a | Source routing |
| **Z-wave** | n/a | Source routing |

previously described routing protocols. LOADng is regarded as a lightweight version of AODV where simplifications were introduced, achieving an enhanced flexibility and performance result. This routing protocol for ad hoc networks can be considered as a candidate for last-mile smart metering applications. More information of LOADng can be found in [75]

## 2.10 Emergent Wireless Solutions

There are other wireless solutions and technologies that can be considered for smart grids but their effective use is still under discussion. So far the presented technologies, which can be regarded as conventional, concern wireless communications between devices within a single hop. As an alternative, multi-hop technologies can be considered to support SG applications, which is the case of the IEEE 802.15.4g, which defines a mesh network solution for smart metering, using a flat network of smart meters. Although the mesh network has already been used in WPANs/ZigBee, namely through the IEEE 802.15.5, this section discusses the use of mesh networks in the last-mile segment which is beyond their scope. This section discusses a wireless mesh alternative to support applications beyond the simple smart metering, where the exploration of enhanced management schemes can allow multi-hop wireless networks to become more flexible and appealing in the SG context.

### 2.10.1 Wireless Mesh Networks

One of such solutions makes use of Wireless Mesh Networks (WMN) as a means to extend the coverage of a wireless network over multiple wireless hops and to provide access to infrastructure networks, wired or wireless. These are networks composed of Mesh Access Points (MAP) organized according to different topologies.

In the last-mile segment of electric grids the deployment of communications networks has been traditionally scarce, meaning that WMNs can in fact be considered as a solution to extend communications networks from other segments, in this case typically from upstream utility related backbone network. It can be regarded as a potentially cost-effective alternative to the long lasting narrowband PLC preference for the electric distribution grid.

The different wireless mesh networks topologies are depicted in Fig. 2.19. In a simple vision the WMN is composed of MAPs that act as End Stations (STA) where the exchanged information is relayed towards an external network by any node as illustrated in Fig. 2.19 (A). A more complex and structured system can implemented with the introduction of a two tiered approach, where higher level MAPs form a mesh network as illustrated in Fig. 2.19 (B). Hence, MAPs form a wireless mesh backbone network to which STA devices are attached. The devices at the lower level communicate directly with a neighbor MAP, which provides access to the mesh network. This allows a scalable and robust higher level mesh network structure ensuring connectivity between STAs and with the external network, through a MAP gateway. An even more complex topology can be implemented in a hybrid approach, were mesh networks are formed at different tiers, with more relaying alternatives, as portrayed in Fig. 2.19 (C).

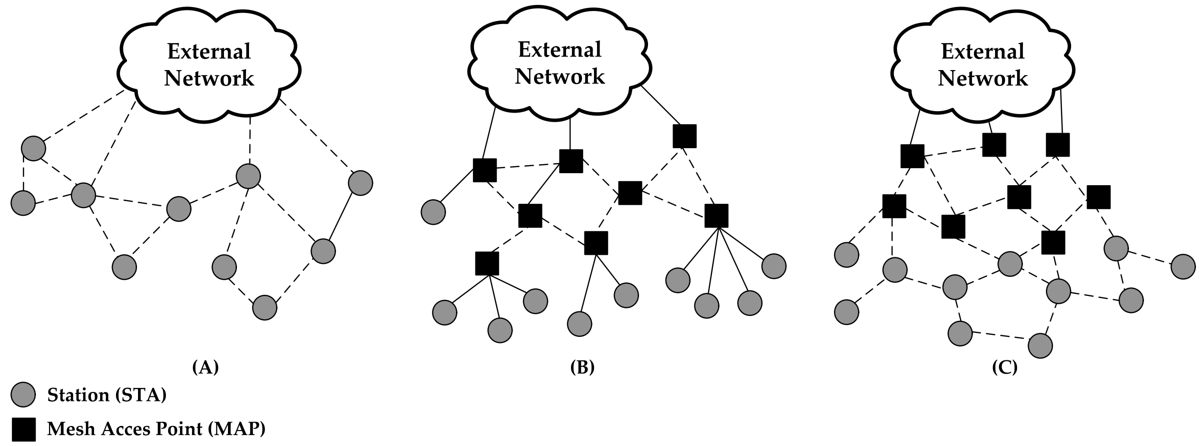



Figure 2.19: Wireless Mesh Networks Topologies

The expected traffic pattern in the distribution segment will most likely involve data aggregation in the upstream direction, from the end devices/customers towards the electric system operator. Such pattern is compatible with WMN implementations where the data traffic concentration is higher near a GW node, which will exchange data with an external network. The data traffic inside the mesh network that is, between end devices itself is expected to be reduced.

Mesh networks offer higher levels of redundancy and robustness in terms of data communications in the event of a link or node loss, either temporary or permanent, or link degradation. Routing algorithms can adapt to dynamic network topologies to deal with variations in communications channel characteristics. The estimation of the best data paths and routing schemes rely on the definition of proper metrics. Despite the advantages of such routing schemes in the flexible operation of these data networks, there is also an increase in the overhead associated with operation signaling required to discover and maintain routes at network level. However mesh networks can be managed at data link level, making use of conventional bridging techniques that rely on simple packet forwarding along a logical tree, although the established routes might not be the best ones. The data traffic between internal pairs of nodes of the

WMN is reduced, meaning that the largest part of the traffic concerns a WMN external entity. As such the mesh gateway node is almost always involved in data exchanged with the exterior, acting as a root node, which makes a spanning tree optimal for this type of traffic.

There are however other drawbacks associated with WMN that need to be addressed with proper mechanisms. One of the issues is the competition among nodes, which is a 1-hop problem typical of 802.11 networks. Since the communication channel is a shared media this issue is usually address by contention based mechanism such as CSMA/CA. Both hidden node and exposed node are also related issues, which are typically addressed through RTS/CTS mechanisms. These issues are aggravated in WMNs due to the existence of multi-hops in the data path, which contribute to the performance degradation of the communications network. In these scenarios the use RTS/CTS can even become counterproductive. Beside the increase in latency another problem is the existence of additional collisions since the interference (inter and intra-flow) phenomena can have impact over several hops. This means that unfairness will occur where nodes farther away from the GW will have to contend more times for accessing the channel. Besides a reduction of the actual network capacity is to be expected, since the spatial contention goes beyond 1-hop. As such, spatial reuse strategies and scheduling schemes are used to mitigate the impact of interference, but this is a challenging process since there is not a clear optimization procedure to adopt, usually meaning that a trade-off between performance and complexity need to be reached. Due to these issues congestion phenomena occurs, especially when large volumes of data are exchanged through the GW node, namely due to data aggregation towards the GW.

Hence, the use of WMNs introduces challenges that need to be tackled to prevent the performance degradation of such networks. Issues like fairness [76], scheduling in terms of fair-sharing [77, 78] or resource optimization [79] and cross-layer mechanisms like scheduling with congestion control [80] are topics of research in the area of WMNs.

There are some characteristics in the distribution segment that may promote and facilitate the use of WMNs to support applications within the context of smart grids. Most communications devices deployed in distribution networks are expected not to have mobility characteristics and the planning for the WMNs can be made in a medium/long term perspective, since major changes will only be introduced when considering expansion or reinforcement of communications networks. Power constraints are very low given the nature of the power grid, but battery support may be required in case survival of communications network is necessary in the event of a power failure or more severe blackout events. The geographic span of last-mile SG communications networks may not require a higher number of mesh nodes, which has clear benefits in terms of data path hop-count and requires less complex management schemes. However the use of WMNs in MV distribution networks may have to deal with larger distances and a significant number of nodes that already include data aggregation of larger data volumes thus requiring higher bandwidth.

### 2.10.2 WiFIX

The growth in broadband services has been stimulating investments in access networks, like those using IEEE 802.11 based technology. On one hand, the success of these solutions in supporting a wide variety of applications has been triggering the exploration of other possible scenarios of application. On the other hand the known limitations in terms of radio range and consequent geographic coverage has posed several challenges when new applications are considered. In fact these limitations are transversal to wireless communications technologies in general; the use of mesh networks is suggested to overcome these limitations at the expense of some performance degradation and routing complexity. Hence, as pointed out in [81], WMNs are a cost-effective solution to extend the coverage of wireless networks, like 802.11. They can also be used as an extension of wired communications network infrastructures.

A proposal for the extension of wired communications networks using simple and efficient WMNs is advanced in [81], which described a solution called WiFIX. This solution is presented as an alternative to the IEEE 802.11s which defines mesh networking within the 802.11 family. The original WiFIX system has evolved [81, 82, 83] and it consists of a simple and efficient tree-based algorithm for stub WMNs that runs over 802.11 legacy MAC. An active tree topology is built, starting from the root node to deal with path auto-configuration issues. Hence, it is possible to run WiFIX over 802.11 compliant wireless cards, by processing the incoming and outgoing data packets without any modification to the 802.11 MAC. Instead an IEEE 802.1D bridging mechanism is used with the addition of a single message protocol scheme. Like those described earlier, a WiFIX WMN is composed of MAPs with bidirectional forwarding capability defining a multi-hop communications infrastructure. These nodes can also act as STAs or GWs ensuring an interface with external and possibly wired backbone networks.

Over WiFIX it is possible to schedule transmissions from each MAP in a master-slave scheme, so that collisions are prevented, but the CSMA/CA mechanism is still active to deal with residual collisions, in particular those involving control packets. One of such examples is a polling-base mechanism through which it is ensured that each node has the same opportunity to transmit a packet.

In order to improve the overall efficiency of a mesh network, like WiFIX, spatial reuse can be exploited. Although this is an orthogonal subject it can be incorporated in WiFIX to increase the performance of the network. The network capacity is one of the examples where spatial could be used to mitigate the degradation with the hop count (e.g., in chain of nodes). It can allow the WMN to reach between 1/4 to 1/3 of the capacity of common wireless channels.

### 2.10.3 Wireless Communications Opportunities for Smart Grids

Some of the scenarios that are likely to be found in SG will raise some challenges for the use of wireless communications in terms of coverage and RF penetration, especially in the aforementioned last-mile segment where a combination of outdoor and indoor communications is often required.

The radio frequency used in wireless communications systems is one of the main characteristics that affect performance in these types of scenarios. The problem is that the available RF spectrum is becoming a scarcer resource for newer applications, like SGs, especially in the sub-GHz segment. Given this constraint the strategy so far has been to conserve or reuse this resource and explore the use of more efficient RF technologies. The use of more convenient frequencies can allow the implementation of cost-effective solutions and less complex planning activities in order to deploy wireless communications infrastructures. One particular example can be found in WMNs, which can largely benefit from the use of technically more favorable radio frequencies, in terms of transmission range, which contributes to the reduction in the number of hops that are necessary to ensure the same level of coverage.

Within the RF reusability spirit, TV White Space (TVWS) communications are considered in [73] for SUNs, where unused locally assigned TV broadcast frequencies are used to convey SG data. The TVWS consists of unused VHF/UHF bands which are licensed to TV broadcasting companies. However, the US Federal Communications Commission (FCC) has recently defined regulations for the use of TVWS where several conditions and restrictions are imposed, which limit the objective of reusing these frequencies. One of such restrictions is associated with the allowable transmission power according to the type of device. However, the main obstacle in the implementation of SUNs in these bands is related with the required geolocation awareness capability that these nodes must have [73]. In the UK, the Office of Communications (Ofcom) is defining the rules for TVWS whereas the Electronic Communications Committee (ECC), which is part of the Conference of European Post and Telecommunications (CEPT), defines the rules in Europe.

In this regard, cognitive radio networks seem to find in TVWS a potential infrastructure to support several applications such as medical, public safety, cellular or smart grids [84]. The use of cognitive radio has been envisaged to increase the efficiency in the use of radio frequency bands. These inefficiencies can be associated with design issues, technological limitations or the intention of regulating entities to protect spectrum allocation, ensuring exclusivity in its usage. The use of cognitive radio requires a coexistence approach since it will operate in scenarios were communications services are deployed, which are referred to as primary services, whereas cognitive radio provides secondary services [85].

Cognitive radio-based networks are thus a potential candidate, as mentioned in [84], to implement the infrastructure for AMI/FAN, with advantages in terms of bandwidth, coverage range and cost. Smart grid communicating devices based on cognitive radio hardware are hence able to access the underutilized spectrum to exchange information. The frequencies associated with TVWS have propagation characteristics that can allow cognitive radio devices to communicate directly with a GW node or in case of a wireless mesh implementation to use less hops to reach the GW node. It also allows a higher degree of penetration within buildings, making it flexible and suitable for last-mile combined indoor and outdoor scenarios.

The IEEE 802.22 standard defines the MAC and PHY layers of point-to-multipoint Wireless Regional Area Networks (WRAN) in the VHF/UHF TV broadcast bands. According to [86] the standard purpose is to enable the use of WRAN devices in diverse geographic areas within TV broadcast bands without interfering with incumbent licensed services. The expected coverage can vary from 10 to 30 km and can reach up to 100 km under exceptional RF propagation conditions. The IEEE 802.11af and IEEE 802.15.4m are current amendments for TVWS, respectively for WLANs and WPANs. A specific coexistence standard for TVWS is defined under IEEE 802.19.1.

Despite the advantages of cognitive radio systems, there are reliability and applicability issues, which are also transverse to other systems that make use of license exempt bands. It can lead to congestion scenarios when cognitive radio devices are operated in a heterogeneous and non-coordinated fashion [84]. These challenges can compromise smart grid applications, especially those depending on real-time requirements; nonetheless, they can be used to implement low-latency data links [87].

The disconnection of analog TV broadcasting systems, which is freeing in large areas a significant amount of RF band within the VHF/UHF spectrum is another opportunity for smart grids [88]. Unlike TVWS and cognitive radio, where a co-existence rationale is used, here specific bands could be assigned to SG applications only, but a generalized dependence on specific regulatory issues that will further define the use of theses frequency bands is still pending. The EU is committed to define a pan-European approach towards SGs implementations [89] where harmonization in terms of the usage of TV analog bands for communications is being considered.

## 2.11 Simulation Tools

To evaluate the impact that different control strategies have within the previously described microgrids and multi-microgrids architectures, it is important to analyze the electric system behavior in steady-state and assess the different transients and dynamics responses. Similarly, it is also important to evaluate the impact that communications systems have, namely due to data losses and delays, in the overall performance of different control strategies envisaged for the distribution network.

The major advantage of using simulation tools is the flexibility in reconfiguring and testing different scenarios, solutions and approaches. It allows the evaluation of the electric and communications networks separately or together.

### 2.11.1 Simulation of Electric Networks

Among the different available simulation tools for power systems the most reputed are PSS/E[9] from Siemens and Eurostag[10] from Tractebel. They are both commercial licensed software versions commonly used in the industry and in academia for technical research, studies and operational assessment of power systems. They incorporate several models for generators (synchronous/asynchronous machines, power converters, etc), transmission lines and loads. They both provide dynamic and static models and allow specific user models to be implemented. It is possible to run in both scripts allow an automated configuration of the electric power systems conditions and potentially allow the interaction with external tools.

### 2.11.2 Simulation of Communications Networks

Network simulation represents one of the evaluation methodologies for development and testing of communications architectures, protocols, technologies and other related topics. The majority of communications network simulators are event-driven. Events are triggered by node activity and the simulator platform defines a list of scheduled events that are processed as the simulation progresses throughout a predefined time interval.

There are a considerable amount of network simulators currently available, which are able to implement a wide variety of communications scenarios and technologies. Overall, they can be divided into industrial/commercial and academic, targeting different users and applications. Given that academic implementations of these simulators have generally no licensing costs and typically provide the source code for open contributions they are deemed as advantageous when compared to commercial solutions. There are several different characteristics sought in communications simulators and the following can be considered to decide over the appropriate solution:

[9] "PSS/E" - http://www.energy.siemens.com/hq/en/services/power-transmission-distribution/power-technologies-international/software-solutions/pss-e.htm
[10] "Eurostag" - http://www.eurostag.be

- Modularity - the source code should take advantage of enhanced features of modern programming languages such as Java, Python or C/C++ like the modular object-based modeling approach;

- Scalability - the increase of the number of nodes or the amount of exchanged data in a communication network to be simulated should be implemented without compromising performance or significantly impacting the development time;

- Performance - the considerable variation of communicating nodes when different scenarios are considered, require that the simulation platform is capable to withstand different numbers of nodes while mitigating the increase in computational effort, e.g., memory usage;

- Documentation - the available simulator documentation and its quality can a considerable impact in the learning curve, allowing a quick development of communications scenario and to tackle the features of the simulation tool in a reasonable time;

- Support - like documentation, support is a key issue since it provides a helpful resource in the development process.

In [90] a complete comparison between the most recent discrete simulators is presented and a benchmark procedure is implemented using a reference network topology for performance assessment. An initial square topology with 16 nodes was used with only one sending node generating a data packet every second. The packet is broadcasted to neighbor nodes which will relay it, adding an extra second delay to emulate local processing, up until the destination node is reached. The performance evaluation was conducted on the following network simulators: ns-2[11], ns-3[12], OMNeT++[13], JiST[14] and SimPy[15]. The results regarding the simulator performance when considering different network sizes, can be found in [90] and are presented also in Fig. 2.20.

Results show that overall both ns-3 and OMNeT++ present the best alternatives in terms of network size, which is envisaged of considerable importance since the communications systems to be simulated in smart grid scenarios can have a significant amount of communicating nodes and various forms of implementation.

### 2.11.3 Integrated Simulation

The combination of electric and communications simulators has been a subject of interest and it has been explored under an integrated simulation scheme, often designated by co-simulation, in the sense of cooperative simulation, or integrated simulation. This topic is not actually new and it has been more intensively researched in the last years. These integrated systems intended initially to combine simulators that were originally conceived to work separately, as such, the main challenge was how to integrate them. The fact that communications simulators are event driven, meaning a discrete processing strategy is used; however electric simulators intend to represent electromagnetic and electromechanic,

[11] "ns-2" - http://www.isi.edu/nsnam/ns
[12] "ns-3" - http://www.nsnam.org
[13] "OMNeT++" - http://www.omnetpp.org
[14] "JiST" - http://jist.ece.cornell.edu
[15] "SimPy" - http://simpy.sourceforge.net

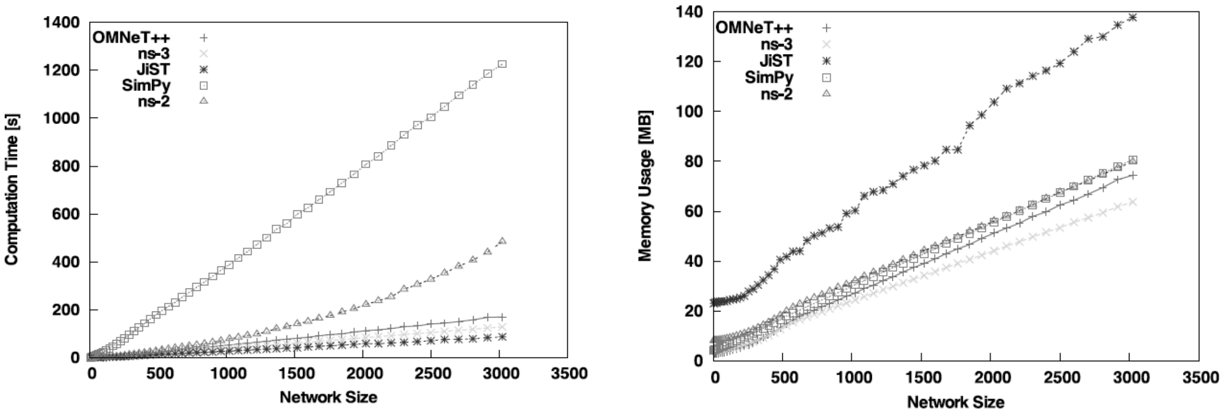



Figure 2.20: Scalability Performance of Simulators

meaning a continuous processing strategy. This can create a mismatch when integrating power systems and communications networks simulators.

One of the first integrated simulating platforms was the EPOCHS framework [91] that uses a federation of simulators: PSCAD/EMTDC for modeling electromagnetic transients, PSLF for modeling electromechanical transients and ns-2 for simulating the communications network. The simulators are managed though the Runtime Infrastructure software module (RTI) that periodically allows them to exchange information thus enabling a synchronization between both processes. It uses an agent based platform for monitoring and control actions in the electric network. The agents are able to exchange data among them.

Since power systems simulators commonly use numerical algorithms to solve differential-algebraic equations that model the system dynamics [92]. This means that the power system simulation can be considered also as a discrete. Hence time step is used, typically small to prevent abrupt changes, to evaluate the system variables behavior. In [92] the Discrete Event System Specification (DEVS) formalism that was introduced to enable the hybrid simulation of electric and communications systems, through means of synchronization of events. Despite the fact that ns-2 is used for simulating communications networks, the electric power system had to be modeled through mathematical equations.

Another co-simulation platform is the PowerNet introduced in [93], which combines Modelica for the power system and ns-2 for the communications. Different synchronization strategies are approached and the selected one was to enslave Modelica to ns-2, in order for the latter to determine all time instants where data exchange between them occurs. The interaction is performed through read/write functions and in terms of simulation time ns-2 is always ahead of Modelica.

A Global Event-Driven Co-Simulation Framework (GECO) is proposed in [94] that also aims, like EPOCHS, to combine power systems and communications networks simulator. The same combination of PSLF and ns-2 is proposed by the authors, but a global event scheduler is proposed. This scheduler defined in GECO avoids the errors introduced by the time-stepped approach of EPOCHS for instance, since power systems and communications simulators are discrete. As such a global event queue is used where the events from the communications simulator are interleaved with the events from the power systems simulators according to their timestamps. The combination of these events is validated through the DEVS formalism. The co-simulation is driven by a sub-component in ns-2. In [94] a comparison between co-simulation platforms, some of them mentioned earlier, is also presented.

Other similar implementations worth mentioning are [95] and [96]. In the first case a combination of ns-2 for the communications and OpenDSS for the electric network is proposed. A real feeder is modeled and a wireless IEEE 802.11 communications network is used to support monitor and control activities. In the second a combination of MATLAB and OMNET++ is used, respectively for the power system and communications. A models with an application and a middleware layers were designed to interact with a support layer, being the latter responsible for interacting with both simulators. In both cases the information regarding the implementation and the synchronization mechanisms used to couple the proposed co-simulation framework is limited.

## 2.12 Overview of Related Projects

In recent years several research projects and other initiatives around the world focused on developing concepts and solutions suitable for the deployment of smart grids. There is a historical perspective regarding the concepts defined in the different projects when addressing the modernization of the electric grid that ranges from the introduction of new control schemes and enhanced architectures that consider distributed actions to improve the electric system efficiency, reliability and security, up to elaborated market structures to support the integration of novel entities in the grid. In between, the basics of smart metering were approached and after successive evolution stages they ended up supporting the expansion of customer and utilities networks towards data exchange in the distribution segment. The following projects chronologically depict the evolution of different concepts currently associated with smart grids, although some of them are contemporary. Given their specific importance some of them will be revisited in the next chapter in the SoA perspective. They provide a context regarding some of the initiatives that address smart grid applications and related issues, while considering communications solutions for the evolving power system.

The projects identified in this section produced relevant state-of-the-art outputs regarding conceptual models, specifications, impact assessment and technology surveys within the context of smart grids.

### 2.12.1 Microgrids

The 2003-2005 "Microgrids - Large Scale Integration of Microgeneration to Low Voltage Networks" project[16], funded by the Fifth Framework Programme (FP5), was the first large European project devoted to the integration of small and modular generation sources in LV distribution networks, thus defining the concept of Microgrid. The main research topics were [97]:

- Development of steady state and dynamic simulation tools;
- Development of local micro source controllers and microgrid central controller;

[16] "Microgrids Project" - http://www.microgrids.eu/micro2000/index.php

- Development of emergency functions;
- Safety and protection assessment;
- Assessment of communications infrastructures and protocols;
- Assessment of regulatory, commercial, economic and environmental issues;
- Development of microgrids laboratory and evaluation of case studies.

The crafted microgrid definition targets the increase of RES penetration and integration of other microsources, while reducing losses with the consequent increase in efficiency, allied with the potential reduction of energy costs for end consumers. The project investigated control, protection, safety and communications infrastructures considering the interconnected and standalone modes of operation of microgrids.

### 2.12.2 More Microgrids

The More Microgrids was a 2006-2009 European R&D project[17], funded by the Sixth Framework Programme (FP6) and led by the National Technical University of Athens, involving research institutions, utilities, system operators and manufacturers. The main objective of the project was to explore the concepts of microgrids developed under the previous Microgrids EU project, aiming at increasing the integration of microgeneration sources in electric grids.

A new hierarchy control layer was defined to handle the management and control of sets of microgrids, in a configuration designated multi-microgrid, and the necessary interconnection with DMS. For that purpose, new microgeneration control schemes were defined associated with specific DER controllers, which would allow the implementation of enhanced control strategies along with the use of advanced communications technologies. The defined control strategies ranged from a centralized scheme down to fully decentralized approaches. The technical and market feasibility of multi-microgrids was evaluated considering the impacts of microgrids in both system operation conditions and infrastructure development [40].

The project highlighted the necessary changes in the distribution management and control and the required market dynamics to integrate the participation of newer entities under an electric grid modernization context.

### 2.12.3 OPEN meter

The OPEN meter was a 2009-2011 Seventh Framework Project (FP7) EU funded project[18], which gathered 19 participants from utilities, manufacturers, research institutions and standards bodies, to develop open standards for smart metering / AMI applications. Coordinated by Iberdrola, the project analyzed market requirements, technologies and standards towards an interoperable vision for advanced metering systems [98]. The most relevant outputs provided by the project can be divided into:

[17] "More Microgrids Project" - http://www.microgrids.eu/index.php
[18] "Open meter Project" - http://www.openmeter.com/

- Identification and specification of requirements (general, technical, regulatory and economic) for advanced multi-metering infrastructure;
- Evaluation and testing of technologies and protocols along with the respective requirements for communications;
- Definition of a system architecture based on OSI layers and multi-metering interfaces;
- Services, architectures and PLC technologies for metering applications.

### 2.12.4 OpenNode

The OpenNode was a 2010-2012 FP7 EU funded project[19], composed of 9 organizations, and as previously referred, takes forward the concepts defined in the OPEN meter projects, but also used outputs and results from the ADDRESS project. The project defined an architecture tailored to interconnect the utility systems and the final customer metering infrastructure, by establishing a control component designated Secondary Substation Node (SSN) and a middleware layer to couple the SSN with the utility DMS. A modular communications architecture based on standardized solutions was proposed to ensure the integration of potentially diverse participants while supporting a massive and distributed embedded system at the distribution level. Different syntactic oriented standards from IEC were adopted considering several segments along with different technologies, according to each considered interface. The project also included prototyping and demonstration activities [99].

The main contributions of the project were:

- Evaluation and definition of requirements;
- Use cases;
- Specification of hardware and software architecture;
- Requirements and specification of middleware architecture;
- Communications architecture and selection of standards.

### 2.12.5 ADDRESS

ADDRESS was a 2008-2012 FP7 EU funded project[20], composed of 25 partners spanning from electricity suppliers, R&D institutions, manufacturers, as well as distribution and transmission network operators. The main objective of this project was to develop a commercial and technical framework towards the active participation of domestic and small commercial customers in electricity markets considering also the provision of services to participants in power grids [100].

The project incorporated the developments introduced by previous projects or programs in the area, like FENIX and DISPOWER, and the IntelliGrid Initiative and IntelliGrid Architecture from EPRI. The topics developed under the project were [100]:

[19] "OpenNode Project" - http://www.opennode.eu/
[20] "ADDRESS Project" - http://www.addressfp7.org/

- Concepts, requirements and scenarios - active demand driven;
- Metering, DSM & DER flexibility management;
- Active grid operation;
- Communications architecture for smart grid with active demand
- Acceptance and benefits of the users;
- Field testing and validation of promising solutions.

### 2.12.6 InovGrid

The InovGrid project was conducted by Portuguese consortium headed by the Portuguese DSO, EDPD, which was formed with the purpose of developing an advanced metering system and define a set of functionalities and devices to provide the distribution grid with the necessary intelligence to face the paradigm change in the electric industry. The advent of the smart grid concept was considered an opportunity for the project to allow the DSO and the associated industry partners developing of the necessary know-how and tools to deal with new forms of management and control of distribution networks. The main objectives of the project were:

- Remote metering platform - to collect and send metering data (consumption or production) to a centralized information system using a communications infrastructure to improve the commercial service of the utility and reduce costs associated with legacy metering strategies;
- Consumer oriented services - to create basic conditions to allow the development of new services that promote an interaction between the customer and the system operator. Enhanced tariff schemes were considered an innovative service that could potentially enable an interaction with customers;
- Market expansion towards the customer - to induce market liberalization and competition promoting the appearance of new market players, like service providers, and new services to be explored in modern distribution grids;
- Demand management - to provide an improved match between supply and demand, reduction of peak demand and efficient use of electric energy by consumers;
- Security of supply - to contribute to an enhanced integration of RES and DG and ensure a diversified portfolio of solutions to improve the security of the electric grid operation;
- Investment assessment - to evaluate investments that lead to more reliable and efficient grids through the use of monitoring, automation and control schemes.

One of the most relevant outputs was the development of a reference architecture, which was designed to accommodate concepts such as distributed management and control, enhanced microgeneration integration and remote energy management. The overall solution of the project was divided into 3 phases. In the first phase a basic set of functionalities tailored for low demand consumers within an architecture framework were incorporated. In the second phase a new set of functionalities for microgeneration integration and public lighting applications was added. Small corrections to the first phase were introduced after a new validation process. The third and final phase included several advanced functionalities towards a complete smart grid vision. The first phase specification of the InovGrid solution was rolled-out in Évora, a medium size city in Portugal, where devices, functionalities and the control architecture were tested in a real-world scenario, providing both a test bed and a demonstration site. This was the largest electric grid modernization pilot in Portugal to date and was designated InovCity.

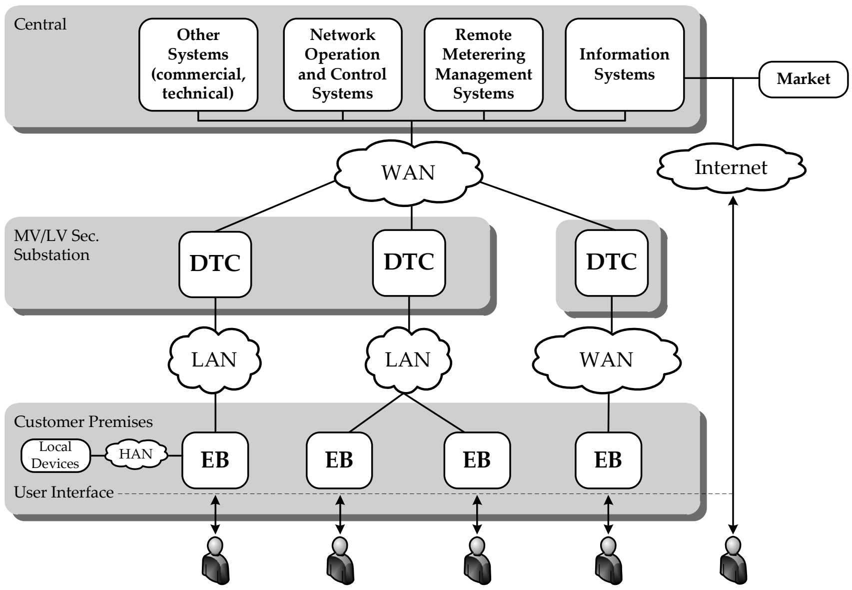



Figure 2.21: InovGrid Reference Architecture - version 1

The reference architecture of InovGrid was inspired in the hierarchical control developed and associated with the microgrid concept with a similar level based structure. The first version of the architecture, illustrated in Fig. 2.21, was the support framework for the first two versions of the InovGrid concept. Three control levels were initially defined with the following managing entities [101]:

- Energy Box (EB) - device to be installed in customer premises with smart metering characteristics. Modules for control, processing and communications were included. It can support features like active and reactive power metering, maximum power in a configurable time period, voltage metering and remote tariff and contracted power change;

- Distribution Transformer Controller (DTC) - device to be installed in MV/LV secondary substation transformer for supervision management and local control of distribution LV networks;

- Centralized System - set of information systems which were developed to support: grid operation and control; remote energy meter management; commercial and technical services.

A support communications infrastructure for the reference architecture was defined to enable data exchange between entities. The preferred technology was narrowband Power Line Communication (PLC) but GPRS was considered in cases where PLC was not feasible due to either technical or economic restrictions. In the backhaul, broadband technologies like ADSL were defined, although GPRS is being pointed out as an alternative in segments where ADSL coverage may not be available. For local control, ZigBee was considered the preferred solution for fast and low-cost deployment of monitoring and control.

The second version of InovGrid reference architecture [102] focused on the integration of a control and management structure at the level of a HV/MV substation. This was introduced in the spirit of the Multi-Microgrid concept in order to take advantage of MV DER to increase system reliability. The architecture and control schemes were updated and a new entity was defined as a Smart Substation Controller (SSC), which introduced a new layer in the previous architecture definition. The main objective of the SSC was to manage the controllable devices within the MV network, among which are the DTCs that, in turn control LV devices. The presence of SSCs allows some of the centralized functions in the DMS to be delegated to this entity to more efficiently coordinate MV devices and at the same time enable the exploration of enhanced and distributed management and control algorithms. The SSC was also defined having in mind a more detailed monitoring scheme that allows for instance fault events to be located and isolated automatically without having to wait for a centralized system to take over, with clear benefits in reducing the time of system restoration services. Coordinated voltage control systems were also considered to benefit from a greater degree of control by managing flexible entities such as MGs. This architecture accounts for a greater interaction with the market domain, where newer services were thought to be easily deployed. The final version of InovGrid architecture, presented in Fig. 2.22, established the possibility of customer participating in system services by allowing the DSO to control, through the customer HAN, the operation of microgeneration devices and flexible loads like EVs.

The integration of EVs was also approached by the project, in which EBs, at a first stage, would allow the DSO, in case of emergency, to override the charging of batteries in order to ensure the system stability [103]. This is an on-off control mechanism triggered by DTCs by sending set-points to EBs only when absolutely necessary. A second stage was explored in which an enhanced control scheme of EV charging is possible, in cases where the customers are willing to provide services to the DSO, and would benefit from financial compensation, for instance in the form of flexible and incentive-oriented tariff schemes. With this approach it was thought that the adoption of smart charging functionalities would be facilitated, thus providing a base for customer participation in ancillary services.

### 2.12.7 MERGE

The MERGE (Mobile Energy Resources in Grids of Electricity)[21] project was conducted by a European consortium of academic institutions and industrial partners aiming at developing new management and control concepts towards the large scale integration of electric vehicles in grids of electricity. The project evaluated the impacts of EV integration on European grids, namely in terms of technical and market operations and in planning activities. The use of distributed control schemes was considered a fundamental aspect in integrating renewable DER and consequently reduce $CO_2$ emissions. Customers are regarded as consumers and producer being EVs the exponent of highly mobile resources that will potentially connect in several locations of the electric grid.

[21] “Mobile Energy Resources in Grids of Electricity” - www.ev-merge.eu

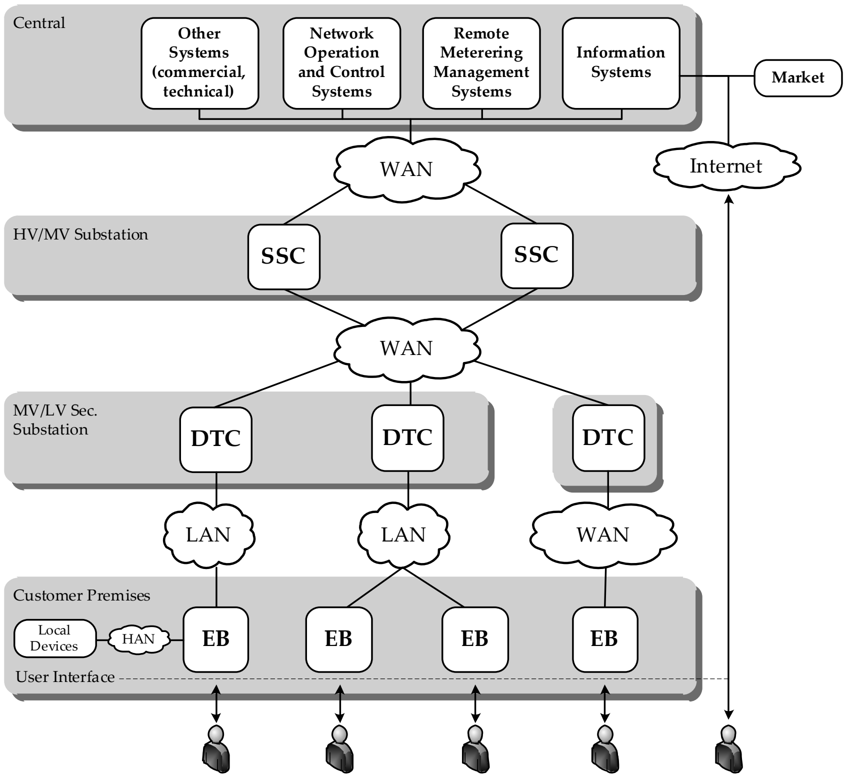



Figure 2.22: InovGrid Reference Architecture - version 2

From the several objectives under the scope of the project the following are associated with Smart Grids and the integration of EVs [104]:

- Specification of interfaces, communications and smart metering technologies for EV integration;
- Extension of MG concepts and control schemes for EV integration individually or in clusters;
- Modeling EV as a storage device;
- Identification of new actors and business models in EV integration.

The specification of intelligent functionalities in the project allowed the assessment and definition of the technologies for a Plug and Play approach when considering the EV connection with the grid. The mobility concept found in other technological segments like the telecommunications industry, where users are able to interact with the infrastructure outside their subscription area, was assessed to determine the viability of such concept with EVs [48].

Smart metering characteristics and functionalities were analyzed and defined, making the smart meters a privileged gateway (GW) for service exchange within the customers premises. The specified functionalities for SM/AMI were grouped in basic and advanced functionalities allowing different services to be explored according to the type of customer. Basic functionalities were defined to target customers that are willing to have an active participation in defining their electric service preferences but at basic level, like selecting different tariff schemes for EV charging. Advanced functionalities were established to allow customers to access more advanced services that rely on an enhanced interaction with utilities or to explore available resources in scenarios such V2G or V2H.

A conceptual framework was defined for EV integration, considering different operation scenarios, control structures and new entities. An agent based control strategy was explored and EV charging modes were defined towards ancillary service provision. A communications solution was implemented in a microgrid in Greece to assess the performance of a multi-agent based solution. The performance of IP-based protocols yielded positive results, especially when using a cabled network to exchange information. Difficulties were identified in using wireless solutions, based on conventional IEEE 802.11, namely due to the need of multiple re-transmissions and in some scenarios there was a persistent loss of connectivity. Findings pointed out that wireless implementations would need a more careful planning and also alternative strategies needed to be explored [105].

The modeling of EVs as energy storage devices was complemented with a thorough analysis of battery technologies. Battery operation was modeled considering a set of variables like charging/discharging cycles, charging rates, internal resistance, lifetime, temperature and aging [106].

From a market perspective new actors and business models associated with EVs were defined at a European level, considering different aspects like the influence of car manufacturers in EV emerging markets, EV related technologies and solutions, legal aspect, historical trends of the automotive industry, battery related services (charging stations, battery swap, battery lease and ancillary services) [107].

### 2.12.8 EDISON

The 2009-2012 Danish EDISON project[22], funded by the Danish Transmission System Operator (TSO) through the FORKSEL research program, aimed at developing solutions towards the integration of EVs. These include network, market and technology tailored for an optimized integration process. Within the project the EV is regarded as a storage device that can potentially contribute to the stabilization of power systems with high RES penetration. Besides the solutions and technology developments, the project envisaged a technical platform for EV demonstration activities.

In EDISON, EV aggregators considered within the virtual power plant approach are used to facilitate the integration in electric grids by motivating EV owners to participate in future electricity market models [108], providing time-coupled metering and billing systems along with incentives to participants. The project also addressed the participation of EVs in ancillary services, such as frequency control.

In terms of communications the project mainly addressed communications standards and solutions for EV communications with the charging infrastructure and the respective functions and interactions and information flows with system operators and market entities, like retailers [109]. IEC 61850, 61851 variants and ISO/IEC 15118 are among the standards considered in EDISON [110].

### 2.12.9 REIVE

REIVE (Smart Grids with Electric Vehicles)[23] was the largest Portuguese project focused on the integration of electric vehicles. The main objectives were the development of a technological framework towards

[22] "EDISON Project" - http://www.edison-net.dk/
[23] "Redes Eléctricas Inteligentes com Veículos Eléctricos" - http://reive.inescporto.pt

the integration of EVs in the Portuguese distribution networks with the identification, specification and testing of innovative solutions within the smart grids concept. The motivation was related with enhanced the technical and market integration of microgeneration and electric vehicles, in order to minimize the need for grid reinforcements and maximize the penetration of renewable energy sources, with high levels of reliability, security and efficiency.

The smart grid concept adopted by the InovGrid project with its reference architecture for distribution networks was used as the basis. The latest version of the InovGrid architecture was the starting point in REIVE to develop advanced management and control strategies oriented towards the inclusion of EV batteries as part of the novel service exchange envisaged for smart grids considering, different technical operating scenarios and business models.

A functional architecture was defined, where the main SG players were identified along with the expected evolution of the distribution grid in a short-term and in a medium to long-term perspectives [111]. In the short term scenario a modest integration of EVs is considered, in which technical operation problems may appear in the distribution segment. Electric vehicles represent a considerable load and, despite the expected conservative integration level, there were distribution networks where issues like line congestion and voltage violation situations did occur. The project considered that in the short-term the EV charging control strategies will be provided by the DSO, in compliance with the national regulation for quality of service. This means that the DSO cannot disconnect EVs in case operational problems arise, since customers will have contracted power services established commercially. This highlighted the importance of an enhanced management algorithm for EV management that allows deferral of investment. In the medium to long-term scenario a significant amount of EV penetration was forecast, with enhanced electricity market integration. A centralized entity responsible for the aggregation of EV customers was considered to allow market representation due to more reliable forecasts of EV demand when managed in clusters. A few challenges were identified with this aggregator entity, since it will have to deal with some uncertainty associated with EV charging, namely the charging place and the amount of power required when charging; nonetheless, EVs are regarded as potential proxies for service exchange with their owners. In this time horizon the normal operation of the grid is market oriented with the ability to establish more complex market negotiation strategies to deal with EV uncertainty, namely through intra-day market correction strategies, being the DSO control structure only activated in case the normal operation is endangered or impossible to sustain.

The functional architecture that was derived considers a hierarchical control structure associated with microgrids and multi-microgrid concepts along with a market structure, as illustrated in Fig. 2.23. The main innovation, when compared with the InovGrid architecture, is the integration of a market oriented structure, where an aggregator entity is responsible for the interaction between the EV owner and the market. The energy box concept was further refined to allow the management of the end-customer EV charging process and provide support for related services. The aggregator entity is composed of a hierarchic structure designed to directly interact with the different levels of the control structure. The Regional Aggregation Unit (RAU) interacts with clusters of EVs at the MV level, in a single-client or multi-client perspective, through a specific energy box for EVs at MV (EB-EVMV). It also interacts with the MV management and control entity, the SSC, for technical information exchange. A similar reasoning was adopted for the LV segment of the distribution network, where the Microgrid Aggregation

Unit (MGAU) interacts with the LV version of the Energy-Box for Electric Vehicles. The MGAU also interacts with the LV control entity, the DTC, for technical information exchange. These interactions are illustrated in Fig. 2.23.

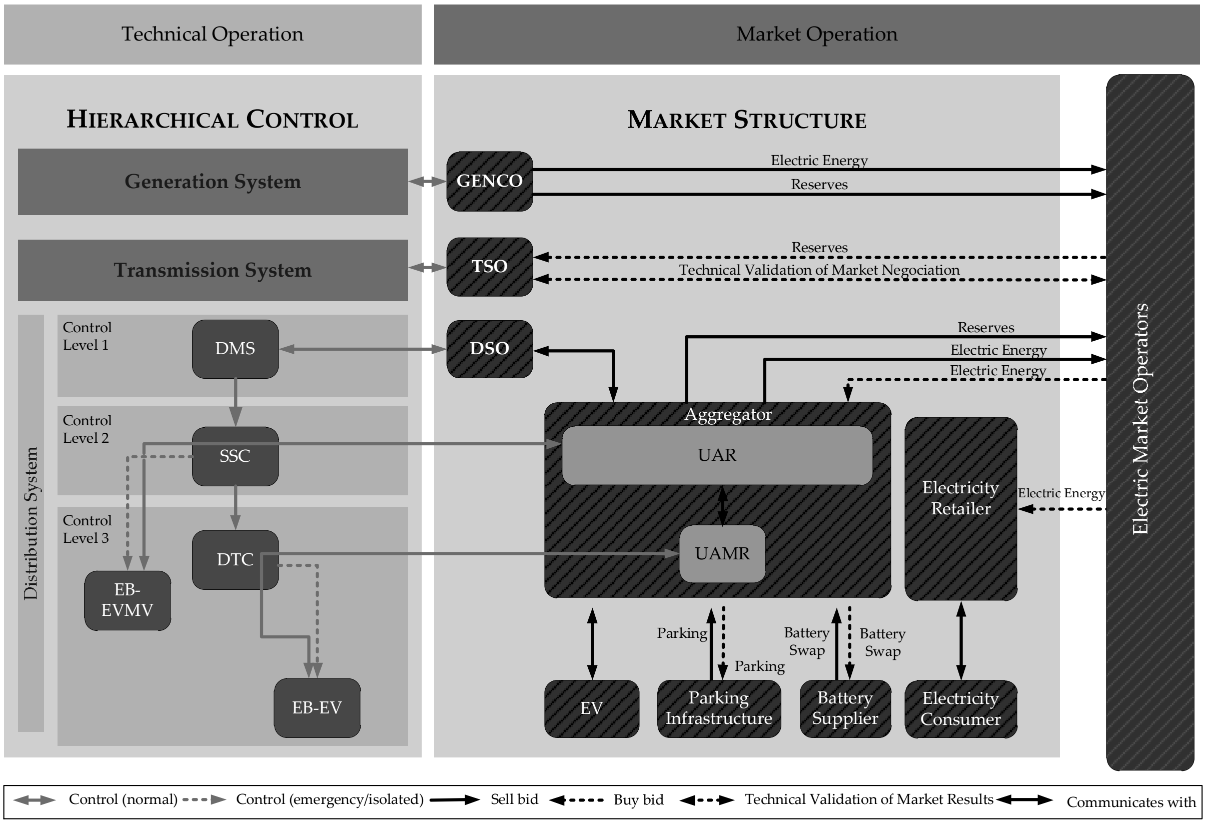



Figure 2.23: REIVE Integrated Architecture

The charging strategies envisioned for the Portuguese distribution grid were considered in the project, namely their impacts on the system operation and the necessary control schemes to tackle them. They are divided in normal and fast charging modes [112]. The fast charging modes ere associated with public charging stations, whereas normal charging modes were associated with both private and public charging points. Given the short time horizon, typically 1h, of fast charging mode, the project considered that only limited control actions would be feasible. On the other hand, since normal charging has a wider time frame, between 8 and 12h, more advanced control schemes were considered. Hence, the normal charging mode was the main basis for the control strategies defined in REIVE, considering the different charging strategies, similar to those mentioned in section 2.6.6.3.

Information flows between commercial aggregators, elements of the distribution system hierarchical control structure and EV customers were identified and characterized [111]. An initial agent based architecture framework was also provided targeting the integration of EVs within the scope of the project. REIVE has also defined analytic tools that were developed for technical impact assessment and quantification, due to the integration of microgeneration and EVs [113, 114]. Communications solutions where also designed and developed considering the main requirement in order to support the different control schemes envisioned for smart grids [115]. Some of these aspects will be detailed throughout this thesis, since they are related with the work that was developed.

## 2.13 Summary and Main Conclusions

Power systems are composed of large interconnected structures that have been designed to operate under safe and reliable conditions. The wide range of phenomena in these systems has led to the definition of operating states according to specific characteristics, which were shown to depend on the interpretation made on each power system. Local and wide area control strategies, which were detailed previously, are centerpieces of power system operation. As such, the use of Microgrids and Multi-Microgrids hierarchical control structures has be shown to provide the distribution networks with the necessary control flexibility in combining centralized and local control strategies. This articulation is supported by a communications infrastructure capable of meeting the requirements for the operation both in interconnected and isolated modes. The latter is typically the most demanding scenario in terms of operation, because not only is the control time frame more restrictive but the communications network need to be capable of operating even when the electric network is down. It has a crucial role in ensuring the successful and safe transition from the interconnected to the isolated mode, and *vice versa*, or in supporting restoration procedures that can be carried out using the MG and MMG concepts.

The integration of EVs in electric power systems and their potential participatory roles (controllable loads or power sources) has been the subject of research namely in the provision of ancillary services and market services associated with the charging process. It is in fact in the market domain that EVs can be managed and controlled by aggregating entities that have to exchange information among services providers, customers and systems operators. The majority of service exchange is based on the day-ahead market or in a more demanding case in a more dynamic intra-day market implementation.

From the main architectural models that were identified in this Chapter there is a considerable amount of similarities namely in terms of the definition of domains, entities/actors and their interaction. The first model where interactions and information exchange were established among different entities was motivated by the implementation of advanced metering infrastructures. Its importance is visible in all the presented models with the incorporation of metering and billing systems. In general, all models establish different types of communications systems, distinguished by the scale and functionalities. A logical and physical segmentation is proposed and a segregation of exchanged data according to the involved domains and entities.

In terms of communications technologies it seems to be clear that the main candidates to support the implementation of private networks capable of implementing the advanced control functionalities envisaged for smart grids can be narrowed down to PLC, for wired networks, and WMNs, for wireless implementations. Other technologies seem to be better suited to support telecom operator networks that provide public services targeting less demanding applications or ensure connectivity where the investment in a private network may not be economically viable. It was shown there are advantages/disadvantages in using either PLC or WMNs for the implementation of last-mile connectivity.

There is a wide variety of simulation tools for electric networks as well as for communications networks that allow the study and evaluation of both types of systems. A recent integration of simulation tools has been explored to cooperatively study communications networks and power systems in a co-simulation environment. However, they often rely on simulation tools that were designed to work alone and a great effort is put in coupling different simulation philosophies. This is a recognized challenge that is differently addressed by existing implementations to deal with the discrete and continuous nature of each simulator, which is responsible for the limited performance of this type of system. The combination of electric and communications simulators has been a subject of interest and it has been explored under an integrated simulation scheme, often designated by co-simulation, in the sense of cooperative simulation, or integrated simulation.

The related projects showed that concepts such as microgrids have been subject of research namely in terms of enhanced control strategies for distribution networks. Concepts like smart metering, functional architectures and the integration of EVs contributed towards the evolution of decentralized control strategies and the emphasized the need for a communications infrastructure to support the associated applications.

# Chapter 3

# Integrated Models and Data Flows for Smart Grids

## 3.1 Introduction

The importance of the modernization process that the electrical grid is undergoing is clear, given the unprecedented changes envisaged under the smart grids paradigm. The communications infrastructure is set to play an important role in integrating existing and newer entities and, as such, some challenges are posed in matching the communications networks with different segments of the electric network.

The integration of distributed energy resources, in particular EVs, potentially brings significant benefits for the grid operation, as highlighted in the previous chapter. However, these benefits come with costs: the need for enhanced control structures and efficient communications networks. The successful implementation of such structures will allow a more dynamic energy market to operate, enabling the creation of new services and functionalities for system operators and end customers but, once again, at the expenses of exchanging additional data exchanged between market and technical domains. The change to a distributed vision for both the control domain, with concepts such as MG and MMG, and the market domain, with aggregating entities defined at different levels, requires the introduction of new information flows. Some of these flows are discussed in this chapter and directed at the Portuguese electric distribution networks, considering an operation model for Smart Grids (SGs) under two time horizon perspectives: short and medium to long term. The content partially results from the specification work performed within the REIVE project.

Many of the novel concepts envisaged for SGs can have a high degree of acceptance by electric system stakeholders like, system operators, after an evaluation and validation process carried out to demonstrate their feasibility. Despite the fact that the process usually starts at a theoretical level of abstraction, a physical implementation, allows a near-real proof of concept of hierarchical technical control schemes with market integration.

This chapter approaches the convergence of electric and data networks towards the integration of different components and stakeholders in a common concept. A functional and operational model is presented considering the most relevant states of operation of the electric system within the technical and market contexts. A logic model is presented for a short term perspective, when a modest penetration of DER and EVs is expected, and for a medium to long term perspective when significant integration will take place. Entities and associated information flows and interactions are established considering the different states of operation, for which use cases are deemed.

## 3.2 Functional and Operational Model

There are a wide variety of functional models envisioned for SGs and some of them were presented in chapter 2. Generally, different states of operation are considered upon which the distribution grid is likely to operate. However, such models must include an enhanced market oriented perspective, in which the grid operation is entirely dictated by negotiation procedures carried out in the market domain, where any deviation from the agreed operation conditions and allowable corrections are highly penalized. Given the complexity found in market schemes to ensure a reliable operation, it is desirable to guarantee that the market operating state is only suspended when no market negotiated solution is capable of preventing the endangerment of the system operation. This leads to the need of considering other states to account for a more pervasive market operation under the smart grids paradigm, where the occurrence of disturbances can trigger specific actions, some of which can still be feasible within the market domain.

In the model proposed in this section, which was also defined in REIVE, the major states are "Normal" and "Emergency" between which two other states were defined according to technical and/or market operational characteristic. These are "Alarm" and "Resolution", which are states where actions are triggered towards the elimination of anomalies. These two states are referred to in [6] as a single state, designated "Abnormal", which is an operational state abstraction over the limit of market operation, where it is still possible to trigger corrective market actions to solve an anomaly under the negotiated market operating conditions. The discrimination introduced here is derived according to the operation context, technical or market, under which the anomaly elimination is performed. In fact, the anomaly or any other defect may need a coordination between technical and market entities. These states and respective transitions are illustrated in Fig. 3.1.

In the "Normal" state the electric system operates without any technical violation or near any operational limit. This is the state where the system is operating as long as possible by definition, and the number of transitions from this state provides indicators related with the robustness of market and technical operation and the consequent ability to settle forecast deviations and solve unexpected events. This state is oriented towards market operation, with information being exchanged between market representatives and end customers and thoroughly validated by system operators.

The "Emergency" is the state in which the operation is near technical limits or an operational index has been exceeded, causing or not technical violations. This is an undesired state of operation since the market operation is disrupted with consequences in terms of negotiated terms and conditions. This state is oriented towards technical operation; the information is exchanged between customers and system operation entities, under market supervision. The emergency state can be triggered if technical restrictions are surpassed with the consequent endangerment of the system. It can also be activated due to market deadlocks or due to the system inability to handle occurring anomalies. The transition to this state, although incurring economical penalties, does not mean that the system undergoes a catastrophic event.

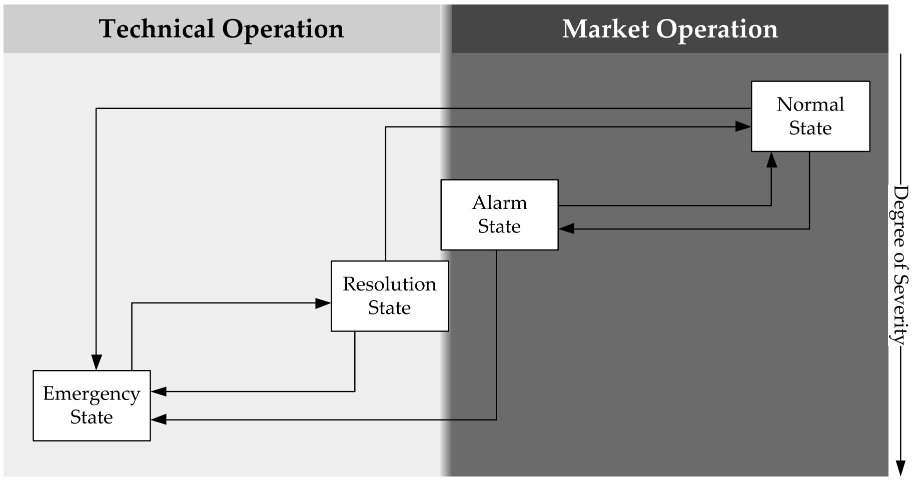



Figure 3.1: Operating States Conceptual Model

In fact, the operation of islanded or isolated systems can be explored in this state, where the survival of islanded systems should be sought and at the same time promote the necessary procedures towards restoring the interconnection. Given the exclusive technical nature of this state further states can be defined to tackle specific scenarios, for instance related with restoration procedures carried out by the system operator after a blackout event. From this state, a set of procedures must be followed to promote the transition to the "Resolution" state; then after a reasonable time interval during which the system is considered to be stable, like in the case of the procedure defined in IEEE 1547, the system operation is able to return to the "Normal" state.

The "Alarm" state is thus triggered whenever an anomaly is detected and the system operator is able to address it under the previously negotiated market terms. However, at this state, there is also the possibility of using intra-day corrective market schemes to help solving more demanding scenarios. If the market successfully addresses and eliminates the anomalies the system returns to "Normal" state after a reasonable period of time. Nevertheless, if the anomaly is not resolved in a specified time interval or if the technical operation is compromised, due for instance to unexpected changes in operating conditions, the "Emergency" state is triggered and the market operation is temporarily suspended until normal operating conditions are reestablished. This way the system operation control structure takes over the operation with the purpose of protecting its main asset which is the distribution grid.

The "Resolution" state is mainly technically oriented, where the system operator is addressing the compromised system operation with the sole purpose of ensuring the necessary conditions for resuming normal operation. In this state the market is aware of the control efforts performed by the technical side and, as such, should jointly participate in the reestablishment of "Normal" operation as smoothly as possible. This means that corrective actions will have to be engaged, which will most likely require new negotiation procedures to enable the successful transition to the "Normal" state. However, if by any reason the system reacts adversely either due to market negotiation failure or to changes in the technical operation that compromise the system security then the "Emergency" state is immediately activated.

It should be noted that this functional model is a macro description and, as such, it allows further alterations during future evolution processes. In fact the state definition is mainly related with procedures carried out under different operating conditions and can be further detailed, modified or adapted to meet specific scenarios, which does not invalidate the high level perspective introduced by this proposal. It is expected, as already mentioned, that with an enhanced participation in market environment of the several stakeholders, the system will usually operate in normal conditions and since transitions outside this state are economically penalizing thus contributing towards the necessary changes, either at market or technical levels, for a more efficient and secure network operation and exploration.

## 3.3 Logic Model

The model advanced in [6, 7] associate a hierarchic perspective both to the technical and market operations. It is proposed an integrated approach of technical and market operations considering novel services introduced by the aggregated control and market participation of electric vehicles. This proposed framework considers an advanced market integration where EV deployment has a relevant impact in the network operation strategies and has already a market representation through the use of aggregator entities that act as market representatives. It conceives mainly the normal and emergency/isolated operating states. The first is market oriented, where the information exchanged among different entities is mainly a result of a market negotiation for the day-ahead operation or through intra-day corrective market operation. In the latter, the market operation is suspended and consequently a hierarchic control structure takes over and proceeds with the necessary changes to drive the system operation into the normal state as quickly as possible.

The advantages in the long term of including these new market players, the aggregators, in managing a significant amount of EV distributed through a wide geographic area, which may include LV and MV distribution networks, is also widely discussed in [6, 7]. This is approached by assigning market responsibilities to aggregators while the distribution system operator will act mainly as a supervising entity that monitors the network operating conditions and only intervenes in extreme scenarios.

This model, however, does not account for a transition period in the integration of EVs, in which the penetration is still incipient with a limited expression in terms of market negotiation. Hence, the market representatives are still limited or typically associated with utilities. There is however a legislative action in Europe to introduce a new stakeholder within the electric power system that is responsible for the market integration of electric mobility customers [116]. This short term perspective should not only accommodate the management and control principles developed under the SG paradigm but promote the integration of EV under a market perspective. Hence, creating the conditions for the long-term perspective where the number of EVs is large enough to introduce a significant impact in the system operation both from a technical and market point of view.

The logical model presented in this section is based on this two-fold approach considering different time horizons: a short term perspective is focused on enabling the grid to accommodate the integration of new entities and services; a long term perspective is focused on enhanced participation of entities like aggregators of EVs in the exchange of market-oriented services. An important issue when defining both perspectives is to ensure the necessary flexibility and modularity to allow future expansions and upgrades in terms of services, technologies and participating entities and domains. As it will be further explained, it is expected that the transition between models will also lead to the evolution of information flows and respective involved entities and targeted data exchange architectures.

### 3.3.1 Short Term Perspective

The short term perspective, despite the different possible implementations, already assumes an advanced interconnection of three domains: technical operation, market operation and customer. This interconnection is mainly justified by the integration of relevant entities such as EVs and representable DGs/DERs. Although they may initially have a modest penetration rate, their power requirements and mobility characteristics are likely to pose technical problems to electric distribution networks [48]. The power involved in the charging process of EVs was shown in [49] to provoke congestion and voltage violations, even when considering a low integration level.

From the technical domain perspective, the introduction of management and control structures based on microgrids and multi-microgrids is assumed to be deployed, thus enabling the distribution operator to implement decentralized control solutions to deal with DERs and EVs. Thus, basic control schemes such as those introduced in InovGrid, where an on/off approach enables the system operators to address technical difficulties while charging EVs, are possible. Nonetheless, more advanced schemes will be necessary to prevent, for instance, unfairness in the provision of charging services by utilities. Customers located in less privileged points of the electric distribution feeder, where technical difficulties are more likely to occur, cannot be negatively discriminated, by preventing the charging process to take place in a normal fashion, or suffer any type of negatively discriminated power curtailment.

The charging services for EVs are a clear example of the need for a short term model in which the system operator will be responsible for the provision of such services. The model presented in Fig. 3.2 depicts the interaction between the previously mentioned domains. The technical operation domain besides interconnecting with the customer domain, to ensure the exchange of information concerning technical operation and management data, also ensures the interconnection with the market domain.

This model assumes that market information exchanged between market entities and end customers is provided by the operation of the hierarchical technical structure. The control structure relies on a communications infrastructure deployed by the distribution system operator for conveying technical information to the end customer management entity (typically designated smart meter or energy box). For that purpose, the technical domain provides specific entities, acting also as aggregation units, with which market representatives interact in order to exchange information with their end customers. These aggregation units can also be used to collect technical information exchanged with market entities for technical validation of market operation. Given the regional scope of control entities defined in the hierarchical control structure within the technical operation domain, in which MGCCs are responsible for management and control of different LV microgrids, whereas CAMCs control and manage MV multi-microgrids, there is also a similar regional approach for the aggregation units provided by the technical operation. The Microgrid Aggregation Unit (MGAU) ensures connectivity services, using the distribution operator communications infrastructure, with LV MG level end customers via their management entity, depicted as Energy Box (EB). The Regional Aggregation Unit (RAU) in turn provides connectivity services with MV level MMG customers.

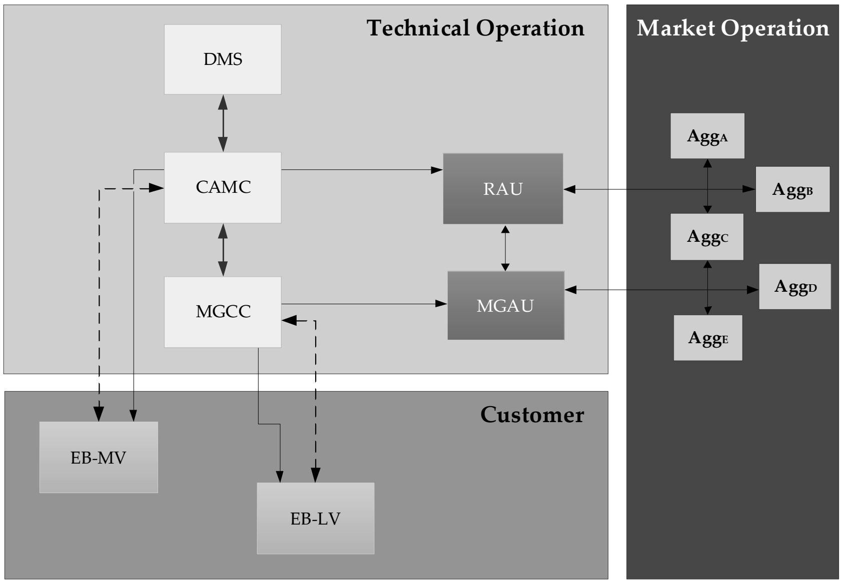



Figure 3.2: Short Term Perspective Model

### 3.3.2 Long Term Perspective

In the long term perspective a large scale integration of EVs is considered. This will lead to the rethinking of the logic model, which will be motivated naturally by the functional separation of the exchanged information within these active distribution networks into technical operation and market related information. Functionally, this separation is illustrated in Fig. 3.3, where the EB is positioned as the centerpiece of the logic model since it represents the only entity that interacts with both technical and market information flows.

The separation of the information flows can be implemented through the physical separation of different communications networks possibly relying on different technologies and deployed solutions; or using a common communications infrastructure but with logical segregation of information that pertains to different entities, similar to the virtual network concept. This separation is likely to appear in a natural fashion since it will represent the support for data exchange considering different business models and operational scopes, although both aiming at the overall objective of supporting smart grid applications.

Market information flows concern the data exchange between end customers, in either LV or MV distribution networks, through their EBs, and their market representatives, in the role of aggregators. As explained in the functional model section, the distribution system is set to operate as much as possible in the market operation, most of the time in the normal state and occasionally in the alarm state. Data concerning tariff schemes, charging strategies, energy consumption profile, energy service participation and other applications is exchanged between market representative entities and consumers/producers. In the market operation domain, aggregators and other market representatives are able to present their offers in terms of supply and demand with the corresponding validation from system operators (transmission and distribution) regarding the operational feasibility of the negotiated market outcomes. The specificity of market operation and associated rules need to be tackled in the sense of ensuring proper rules and

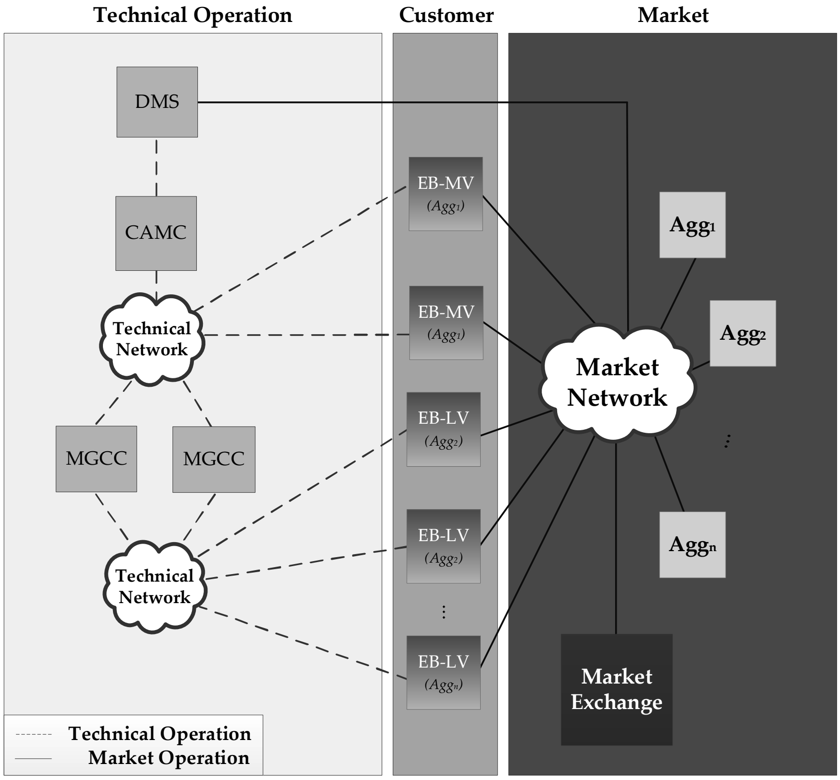



Figure 3.3: Long Term Model

regulations, which are clearly important since they can have a benefit in promoting more dynamic market operation. There is already a considerable work conducted in this specific area that deals with the introduction of new market oriented services and operation mechanisms envisioned for SGs to support DR and DER integration [117] and general ancillary services [118]. However, this is typically approached at the transmission level. It is recognized the importance of integrating novel market models and applications for the distribution but the discussion regarding future implementations, like those presented in EDISON project considering EVs [108], are beyond the scope of the model presented in this section.

Despite these future implementations of market operation models, currently the most demanding time horizon for market operation is 15 minutes. This time frame can be used to ensure a resolutive market operation within the previously defined “Alarm” state. This time period for market negotiation means that 96 negotiation periods are to be carried out. The increase in the volume of information when compared with larger integration periods, like the hourly model currently defined in Portugal, is by itself significant but there is also the increase associated with the integration of a higher number of entities that can potentially participate in electricity markets. Despite this increase in terms of negotiation periods, in which market participants will have to collect the necessary information from their constituents and present their offers into the market, this is carried out in the day-ahead perspective. After the market negotiations are finished, in which the system operators were called to technically validate the proposals, the market aggregators and other representatives will typically have until 0h00 of the following day to notify their customers/producers of their role in implementing the negotiated outcome.

Technical information flows concerning the data exchange conducted within the hierarchical structure presented in Fig. 3.3 are aligned with the MG and MMG concepts. This operational structure plays a monitoring and supervisory surveillance role as long as the system remains operating under the market conditions as defined in the functional model section. It will actively operate in case of technical difficulties, which can lead the systems towards the emergency state of operation, and will result in the suppression of the market operation. As long as the market operation is enforced, which is expected to be the longest possible, the monitoring and supervision information flows can be divided into: bottom-up, originated at hierarchically lower entities in a periodic fashion; and top-down originated at hierarchically higher entities and performed by-request. As such, the distribution operator should ideally ensure the necessary level of surveillance and observability so that when it is called upon taking control of the network it has access to as much information as possible involving the largest number of monitoring devices. This information should also be up-to-date, enabling a more efficient control strategy to be deployed. Despite this ideal scenario where full observability is desirable it should be considered that such scenario is unlike in reality; limitations in communications systems can also contribute negatively to the process of collecting this information.

The time horizon associated with technical operation flows is expected to have the highest and stringent requirements when operating in the emergency state. The market interactions are suspended and the DSO hierarchical control structure has to trigger the collection of information from the different devices under its control, which is the case of EBs. The impact of the exchanged information is very high and it can ultimately be responsible for the survival of parts or even the whole distribution network. As such information reliability indices should be the highest possible and the associated latency as small as possible. However, it is not expected that control actions triggered by the hierarchic structure will have timing requirements as stringent as those found on local control systems or anywhere near electric protective schemes, which can easily reach values below the second. Moreover, it is also unlikely that the same control flows exceed the time horizon defined for reserve systems, namely in their secondary and tertiary control schemes, meaning that the time interval for control actions to take place can range from 30 seconds up to 15 minutes. The excessive dependence on control schemes based on a hierarchical structure can lead to too ambitious requirements to be imposed over the communications infrastructure. It is reasonable to explore more viable alternatives derived from the expected dissemination of DG and DER with enhanced control capabilities.

The technical operation flows can also include communications within the hierarchical control structure resulting from market operations. These include in a generalized and periodic fashion all the entities participating in the day-ahead market negotiation and occasionally involve specific entities associated with intra-diary and restorative markets, usually in a 15 minutes time frame.

### 3.3.3 Rationale for Information Segregation

There are a number of reasons that justify the separation of the technical and market information flows, which can be associated with the evolution of the logic model. One of them has to do with the fact that the exchanged information has clear different scopes, since it concerns on one hand market participants and on the other the system operator entities pertaining to the hierarchical control structure. Another reason can be found on the different requirements that both information flows have, namely in terms of latency, reliability and bandwidth. These communications requirements have obvious implications both in architectural and technological aspects that have to be considered when designing and implementing communications solutions capable of meeting the desired QoS indices.

Although it is admissible that on the short term the communications infrastructure of the system operator is available for the exchange of information related with market operation, it is not expected a particular interest by the DSO to keep ensuring this connectivity. Furthermore, significant investment could be necessary for its communications infrastructure to handle the expected increase of traffic due to the connection of electric vehicles to information networks. Unless there is an economical incentive or a regulatory enforcement, the DSO is not likely to over-invest and maintain a communications network to support the exchange of information that in the long term will potentially be outside its typical business model. There are also different expectations that DSOs put on the communications infrastructures that needs to be considered. At present the technical operation requirements in terms of communications for the electric distribution network are still limited. In fact, communications systems are being deployed for applications such as smart metering and raw management and control, with specific technologies and architectures being selected for that purpose.

It is reasonable to expect that, unless any legal or regulatory policy is set, the commercial representative, in the figure of the aggregator, becomes responsible for ensuring the necessary connectivity with its represented customers, through their EBs. When considering the data volumes that will be associated with market information flows and the non-real-time characteristics associated with this information exchange, one finds that the requirements are not significantly different from those of other communications services currently supported by telecommunications operators using broadband networks to provide for instance Internet services. Hence, it seems reasonable to consider that the participation of customers in the market environment through their aggregators, as commercial representatives, can be performed using the same Internet based solutions as those provided by telecommunications operators. Since market information exchanged between the customer and the aggregator does not directly concern the operation of distribution system, it is admissible that the customer provides the necessary communications access in order to exchange information with a market representative namely through ADSL, coax cable, fiber or a similar Internet access solution. Such vision does not seem to collide with service access already found in other cases where the customer uses an Internet access service to manually report electric metering information to the service provider or access other types of services like e-banking.

Similarly, it is up to the DSO to implement a communications infrastructure that ensures the necessary requirements for the advanced control strategies under the smart grid paradigm providing high reliability indices and reduced latency for real-time or near real-time services. This will allow the DSO to protect its most important asset, which is the distribution network, by implementing the necessary management and control strategies along with the required security schemes. It will also allow the DSO ensuring that in case of a sporadic emergency event that leads to market operation suspension, the communications infrastructure is able to support the necessary recovery strategies that allows a fast transition to the normal state. The information segregation is also advocated in reference models like those defined by NIST or SGAM, which were presented previously, where some exchange of information between domains are considered to be made through public Internet networks.

## 3.4 Entities

The entities previously considered in short and long term perspectives are distributed over three domains, which are aligned with those also defined in the NIST model: Operations (Technical Operation), Markets (Market Operation) and Customer.

The entities defined under the technical operation scope pertain to the distribution system operation under a hierarchical architecture based on the MG and MMG concepts:

- DMS - Centralized management entity that incorporates a SCADA system enabling automatic and manual operation and control over the entities below. It is also the head of the interaction of the system operator with the market operation;

- CAMC - Heads the management and control of MV distribution network elements like DERs, controllable loads, medium voltage EBs and MGs through their MGCCs;

- MGCC - Controls and manages the controllable devices connected to the LV distribution network, among which are low voltage EBs.

For the customer operation domain, the considered entities are mainly energy boxes, which can be regarded as local energy management systems derived from smart metering infrastructures; they can be divided in two categories:

- EB MV - medium voltage energy box, which intermediates system monitoring and control requests, usually between CAMCs and local controllers and monitoring devices. It will also interact with market representatives, directly or through a service based entity provided by the serving utility. Among the local controllers managed by these EBs is the Cluster Vehicle Controllers (CVC), which are responsible for managing and controlling groups of EVs, like in fleet management systems, parking lots or in public charging systems.

- EB LV - low voltage energy box that acts as a domestic gateway conveying the necessary monitoring and control data, usually to an MGCC or a concentration unit, from local metering and control devices. It will also interact with market representatives, directly or through a service based entity provided by the serving utility. Among the available local controllers, the Vehicle Controller (VC) is highlighted due to the set of functionalities it implements to allow the management and control of the connected electric vehicle.

In the market domain the key element in the defined architecture is the aggregator, which is a commercial representative of a group of customers. It can also be regarded as a representative of groups of specific controllable devices, which is the case of EVs. These entities are responsible for market operations, like supply and demand offers, and the necessary acquisition of information from their customers, so that their forecasting tools can allow an enhanced participation in the market. Depending on the model, they can directly exchange information with customers or may use utility communications infrastructure to convey that data. As such, within the technical operation domain there are entities that ensure that market information is securely exchanged between aggregators and end customers:

- RAU - represents the regional aggregation level of customers that include industrial, commercial and other MV customers that have a significant impact on the MV distribution network; it is responsible for conveying market information between EBs and the commercial representative;
- MGAU - represents the microgrid aggregation level of customers and is responsible for the market related data exchanged between LV EBs and the commercial representative.

## 3.5 Information Flows

According to the functional and logical models set previously, the classification of information flows is derived in this section along with some of the typical use cases where, the involved flows and respective entities are exemplified according to specific purposes. The presented flows are based on functional interaction between entities, but unlike in the models advanced by NIST there is no distinction between intra and inter-domain flows. It is assumed the short-term perspective previously discussed but the extrapolation for the long-term is straightforward considering the incorporation of entities, such as MGAU and RAU, directly into aggregators, which will directly interact with the DSO hierarchical control architecture.

The set of use cases were considered in this section to exemplify the interactions between entities and the involved information flows to support a determined application.

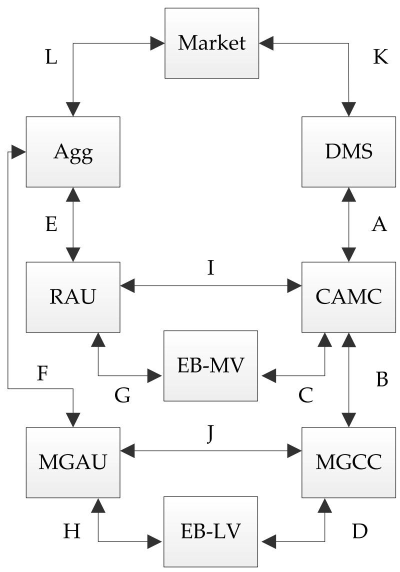



Figure 3.4: Entities and Flows

### 3.5.1 Characterization of Flow

The interaction of different entities within the logical model, which is supported by the defined functional state model, relies on the information exchange among them. In order to facilitate the interpretation of the flows defined in this section, the “Alarm” and “Resolution” states previously mentioned are addressed together in a resolution operation case for simplicity, where actions are taken towards the convergence to the normal state. The remainder states are approached considering respectively the normal and emergency operations. Hence, as illustrated in Fig. 3.4, the flows can be defined as:

- DMS - CAMC – Flow A:
  - Normal Operation - The CAMC periodically reports to the DMS the relevant information (metering, state, etc.) concerning the MV network operation. The DMS is able to request this information asynchronously;
  - Emergency Operation - The CAMC reports at shorter periods information pertaining to the affected MV network part, due to an upstream or downstream disturbance event. The DMS is able to asynchronously send control set-points to enable a secure operation from a centralized point of view, since market operation is suspended;
  - Resolution Operation - The CAMC reports at shorter periods information pertaining to the MV network under its supervision to enable market resolution or restoration. The DMS validates any market decision that resulted from intra-day negotiation, and authenticates requests received by market entities.
- CAMC - MGCC – Flow B:
  - Normal Operation - The MGCC periodically reports to the CAMC the relevant data concerning its microgrid operating state. The CAMC can request state information asynchronously;
  - Emergency Operation - The MGCC reports at shorter periods information regarding the affected LV microgrid due to an upstream or downstream disturbance event with the availability in terms of possible load curtailment or available generation capacity. The CAMC is able to issue control set-points to the several MGCCs according to the control algorithms, knowing beforehand their expected feasibility, in order to secure or restore the operation without any market intervention;
  - Resolution Operation - The MGCC reports information at shorter periods regarding the LV network under its supervision to enable market resolution action or towards the restoration of market operation. The market decisions occurring in the intra-day frame are technically validated by the system operator structure, which can in part be executed upstream by the CAMC. As long as market conditions are maintained no control set-point will be issued by the CAMC; otherwise, the emergency operation will be activated.
- CAMC - EB-MV – Flow C:
  - Normal Operation - The EB periodically reports to the CAMC the relevant variables for monitoring purposes regarding the interconnection within the MV distribution network. A particular case arises when EBs aggregate clusters of EVs, which may represent a very specific MG, where operational data is sent to the CAMC like in the previous flow. The CAMC can asynchronously request monitoring data from MV EBs;

  - Emergency Operation - The EB-MV reports to CAMC, at shorter periods, information regarding the operational state of the controlled portfolio under its supervision and the possibility to curtail/increase load or inject power into the grid to handle upstream disturbances. The CAMC is able to issue control set-points;
  - Resolution Operation - The EB-MV reports information at shorter periods regarding the portfolio under its supervision to enable market resolution actions or restoration of market operation. Market decisions occurring in the intra-day scope are technically validated by the system operation, which can in part be executed by the CAMC. As long as market conditions are maintained no direct control set-point will be issued by the CAMC, forwarding only market set-points.

- MGCC - EB-LV – Flow D:
  - Normal Operation - The EB-LV periodically reports to the MGCC relevant variables for monitoring purposes of available and controllable portfolio. The MGCC can asynchronously request monitoring data;
  - Emergency Operation - The EB-LV reports to the MGCC, at shorter periods, with information regarding the operational state of the controllable and non-controllable devices under its supervision, mainly regarding the available load variation and potentially available generation resources. The MGCC asynchronously issues feasible operation and control set-points according to the availability of the participating devices.
  - Resolution Operation - The EB-LV reports information at shorter periods regarding the available controllable energetic portfolio in order to allow market resolution actions or restoration of market operation. The MGCC sends information to EB-LVs in order to technically validate any incoming market decisions within the intra-day negotiation scope. As long as market conditions are maintained no direct control set-point will be issued by the MGCC; it will only forward market set-points.

- Agg - RAU – Flow E:
  - Normal Operation - The RAU periodically reports to the aggregator the information about its assigned MV customers regarding operating status. The aggregator is able to issue power set-points, via RAU, to its MV customers, which were previously negotiated. These set-points can be sent in periods as small as 15 minutes, considering the currently fine grained intra-day market operation requirements, and they are continuously validated through the corresponding system operator assigned entity which is the CAMC. The RAU can also send asynchronous data requests to customers to fine tune the market operation;
  - Emergency Operation - Under emergency operation this information flow is suspended, being resumed when resolution or normal states are reached. This suspension will occur typically after a disturbance that can cause a potential network operation risk or due to the inability to implement negotiated market operations;

- Resolution Operation - If market operation is feasible the aggregator is able to asynchronously send set-points to its MV customers, via the RAU, to deal with unexpected changes in operation conditions or as part of a reconciliation strategy towards the return to the normal state. Theses set-points are sent under the day-ahead reconciliatory negotiation or the intra-day market negotiation. The RAU reports periodically to the aggregator information about the state of the respective MV customers.

- Agg - MGAU – Flow F:
  - Normal Operation - The MGAU periodically reports to the aggregator the information about its assigned LV customers regarding operating state. The aggregator is able to issue power set-points, via MGAU, to its LV customers which were previously negotiated. These set-points can be sent in periods as small as 15 minutes, considering the currently fine grained market operation requirements, and they are continuously validated through the corresponding system operator assigned entity, which is the MGCC. The MGAU can also send asynchronous data requests to customers within market operation;
  - Emergency Operation - This flow is suspended while emergency operation is enforced due to the reasons presented in flow E.
  - Resolution Operation - If market operation is feasible the aggregator is able to asynchronously send set-points to its LV customers, via the MGAU, to deal with unexpected changes in operation conditions. Theses set-points are sent under the day-ahead reconciliatory negotiation or the intra-day market negotiation. The MGAU periodically reports to the aggregator information about the state of the respective LV customers status.

- RAU - EB-MV – Flow G:
  - Normal Operation - The EB-MV periodically reports to the RAU its customer information regarding operating state, to be forwarded to the respective aggregator representative. The RAU forwards previously negotiated power set-points, to target EB-MVs. These set-points can be forwarded in periods as small as 15 minutes, considering the most demanding intra-day market operation requirements. The RAU can also forward asynchronous data requests to EB-MVs to fine tune the market operation, requested by specific aggregators;
  - Emergency Operation - Under emergency operation this information flow is suspended, being resumed when resolution or normal operation modes are reached. This suspension will occur typically after a disturbance that can cause a potential network operation risk or due to the inability to implement negotiated market operations;
  - Resolution Operation - If market operation is feasible, the RAU forwards asynchronous set-points from the aggregator to its MV customers, to deal with unexpected changes in operation conditions. Theses set-points are sent under the day-ahead reconciliatory negotiation or the intra-day market negotiation. The EB-MV periodically reports to the aggregator, via RAU, customer monitoring information.

- MGAU - EB-LV – Flow H:

- Normal Operation - The EB-LV periodically reports to the MGAU its customer information regarding operating state, to be forwarded to the respective aggregator. The MGAU forwards previously negotiated power set-points, to target EB-LVs. These set-points can be forwarded in periods as small as 15 minutes, considering the currently fine grained market operation requirements. The MGAU can also forward asynchronous data requests to EB-MV to fine tune the market operation, requested by specific aggregators;
- Emergency Operation - Under emergency operation this information flow is suspended, being resumed when resolution or normal operation modes are reached, similar to flow G;
- Resolution Operation - If market operation is feasible the MGAU forwards asynchronous set-points from the aggregator to its MV customers, to deal with unexpected changes in operation conditions. Theses set-points are sent under the day-ahead reconciliatory negotiation or the intra-day market negotiation. The EB-LV periodically reports to the aggregator, via MGAU, information regarding the customer state.

• RAU - CAMC – Flow I:

  - Normal Operation - The RAU periodically informs the CAMC of the power set-points exchanged between the aggregator and its MV customers under market operating conditions and the CAMC will in turn validate the operational feasibility of those actions. This information flow is important since it will accommodate variations in the market negotiated conditions of the previous day;
  - Emergency Operation - Under emergency operation the market exchange information flows are suspended and the CAMC will asynchronously inform the market aggregators, via the RAU, of the planned activities to restore the market operation and the expected system conditions leading the resolution phase in the affected MV distribution networks. There is no market related information exchanged between RAU and CAMC;
  - Resolution Operation - If in the event of a disturbance it is feasible to address this fault under market conditions, the CAMC exchanges information with aggregators via RAU in order to find a quick and cost effective strategy to be employed. The RAU will inform the CAMC of the collected information of each aggregator willing to participate in the resolution of the detected disturbance, under the day-ahead market or the reconciliatory intra-day negotiation. The RAU will issue proper market set-points to the respective EB-MVs. If the market operation was not feasible the resolution state will activate the necessary technical procedures that allow the system to return from the emergency to the normal market state of operation. As such, market information exchange is suspended, and the CAMC will inform the aggregators via RAU of the expected operating conditions once normal/market operation is reestablished;

• MGAU - MGCC – Flow J:

  - Normal Operation - The MGAU periodically informs the MGCC of the power set-points exchanged between aggregators and their MV customers under market operating conditions and the MGCC will in turn validate the operational feasibility of those actions. This information flow is important since it will accommodate variations in the market negotiated conditions of the previous day;

- Emergency Operation - Under emergency operation, the market exchange information flows are suspended and the MGCC will asynchronously inform the market aggregators, via the MGAU, of the planned activities to restore the market operation and the expected system conditions leading to the resolution phase in the affected LV distribution networks. There is no market related information exchanged between MGAU and MGCC;
- Resolution Operation - If in the event of a disturbance it is feasible to address this fault under market conditions, the MGCC exchanges information with aggregators via MGAU in order to find a quick and cost effective strategy to be employed. The MGAU will inform the MGCC of the collected information of each aggregator willing to participate in the resolution of the detected disturbance, under the day-ahead market or the reconciliatory intra-day negotiation. The MGAU will issue proper market set-points to the respective EB-LVs. If the market operation was not feasible then the resolution state will activate the strategy to return to market operation from emergency operation, where market information exchange was suspended. As such, the MGCC will inform the aggregators via MGAU of the expected operating conditions once normal/market operation is reestablished;

- Market - DMS and Market - Agg – Flows K and L:
  - Normal Operation - From the aggregators side the information exchange contains the bids for the day-ahead market negotiation process. From the DMS side the information exchange presents the forecasts of the operating conditions for the distribution networks and provide a validation of the market negotiated bids, ensuring a feasible and secure market oriented operation;
  - Emergency Operation - The DMS informs the market of the occurrence of a disturbance in the distribution networks. It informs the market of the affected networks (LV and/or MV) and the envisaged restoration procedures with a forecast of the operating conditions when the disturbance is addressed. The aggregators are informed of market suspension;
  - Resolution Operation - The convergence towards the normal operation requires the DMS to inform the market of the expected operating system conditions. If the system resolution operation requires a renegotiation process the market will require aggregators to present their bids in an intra-day market operation scheme, where it will technically validate the proposals with the DMS. If the resolution operation does not require renegotiation, beyond the performed negotiation within the day-ahead market, the market informs the aggregators of the feasible set-point operations for all periods.

### 3.5.2 Use Cases

The use cases presented here constitute examples of the information flows expected to be exchanged between the different entities defined earlier, once again considering the aforementioned short-term integration. It should be noted, however, that the presented sequence diagrams for each use-case are simplified. The expected information exchange in each use case is very likely to be far more complex. Nonetheless, it intends to represent the dynamics involved in an integrated technical and market operation. It is also important to notice that some of the information flows represented in the sequence diagrams may not occur sequentially in the sense that some of them may take place in parallel, in case the communications infrastructure or the involved entities allow it. The sequence of notifications can vary when considering different scopes and operating conditions.

From the use cases considered within this scope of section only two of them will be presented to avoid an unnecessarily heavy description: the normal and emergency. Appendix B presents the simplified market negotiation use-case, with the day-ahead and intra-day negotiations, along with the overall use-case, where a transition over all of different states of the functional and operational model defined previously.

For simplicity, in all sequence diagrams, only one EB entity is considered representing generically the different versions of the EBs, namely those concerning the MV and LV customers. The differentiation will be pointed out in the message exchange description. In the normal operation a market oriented information exchange is illustrated where it is assumed that a successful day-ahead negotiation scheme was already carried out in the previous day and a snapshot of the implementation is presented.

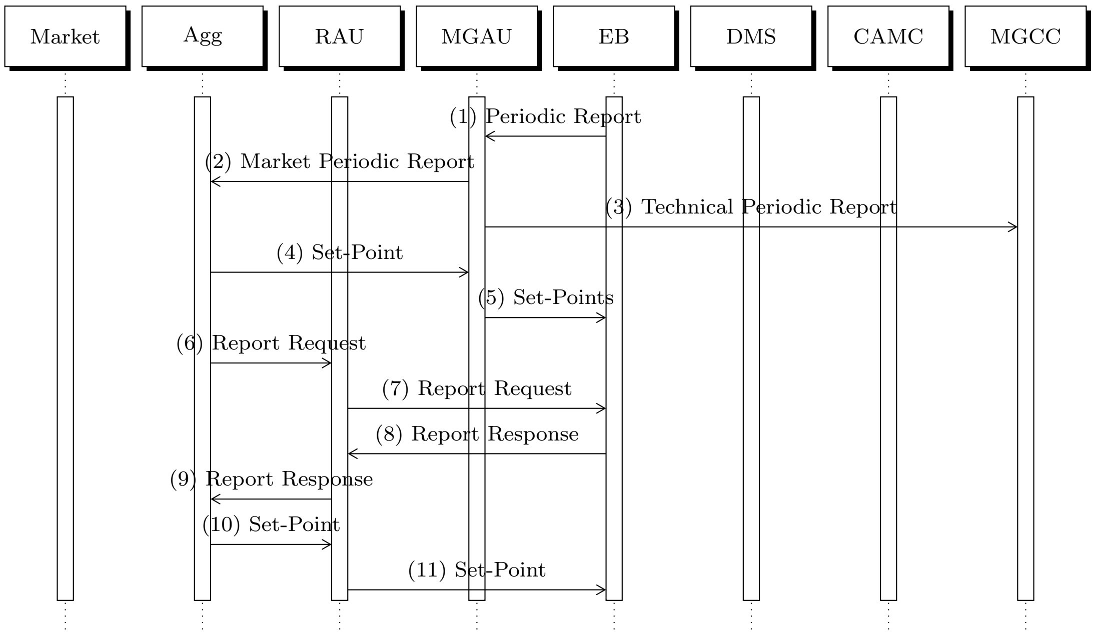



Figure 3.5: Normal Operation State

The information exchange concerning the normal operation is depicted in Fig. 3.5 with the following sequence:

1. The EB issues a periodic report to the MGAU;
2. The MGAU forwards market related information from the received periodic report to a specific aggregator;
3. The technical related periodic report information is forward from the MGAU to the MGCC;

4. The aggregator issues market negotiated set-points to their LV customers through the MGAU;
5. The MGAU forwards the set-points to the respective EBs;
6. A report request is issued (asynchronously) by the aggregator to one or more MV customers via RAU. This report can be due to changes in the operation conditions when compared to the forecast made by the aggregator for the current day. Aggregators can adjust their operation according to the contracted conditions established with their customers in order to ensure that the market conditions negotiated also with the DSO in the previous day are kept; otherwise they may incur in penalties;
7. The RAU forwards the report request;
8. The target EB-MV issues a report response to their aggregator through the RAU;
9. The RAU forwards the report response to the respective aggregator;
10. The aggregator issues one or more set-points to their MV customers according to the received report information;
11. The RAU forwards the set-points to the respective MV customers.

In emergency operation the market information exchange is suspended due to a disturbance event with a significant impact on the electric grid operation, making it unfeasible to address such event in market conditions. The impossibility of ensuring market operation can be due to several reasons, such as a significant deviation of the negotiated conditions in the previous day or a violation of a technical restriction endangering the security of the distribution operation. This state assumes that no intra-day market negotiation solution can feasibly handle the disturbance, which means that the involved technical operation entities are called upon to secure the system operation.

The information exchange concerning the emergency operation is depicted in Fig. 3.6, where the following sequence is considered:

1. A disturbance is detected in a multi-microgrid level and the CAMC is aware of the fault occurrence. The CAMC informs the DMS of the occurrence of the fault which can have impact beyond the affected MG, although in this example it is assumed that the disturbance impacts the MV level;
2. The CAMC informs the affected MGs managing entities, that is, the MGCCs, of the disturbance. This message can also convey set-points for MGCCs in order to immediately handle the consequences of the disturbance in the LV operation;
3. The CAMC informs the MV EBs of the disturbance via RAU. This may also include set-point for EBs to participate in mitigating the impacts of the disturbance event;
4. The RAU forwards to EB-MVs the disturbance detection information, along with potential immediate set-points;
5. The RAU informs the affected aggregators of the temporary suspension of market operation while the emergency operation is active;

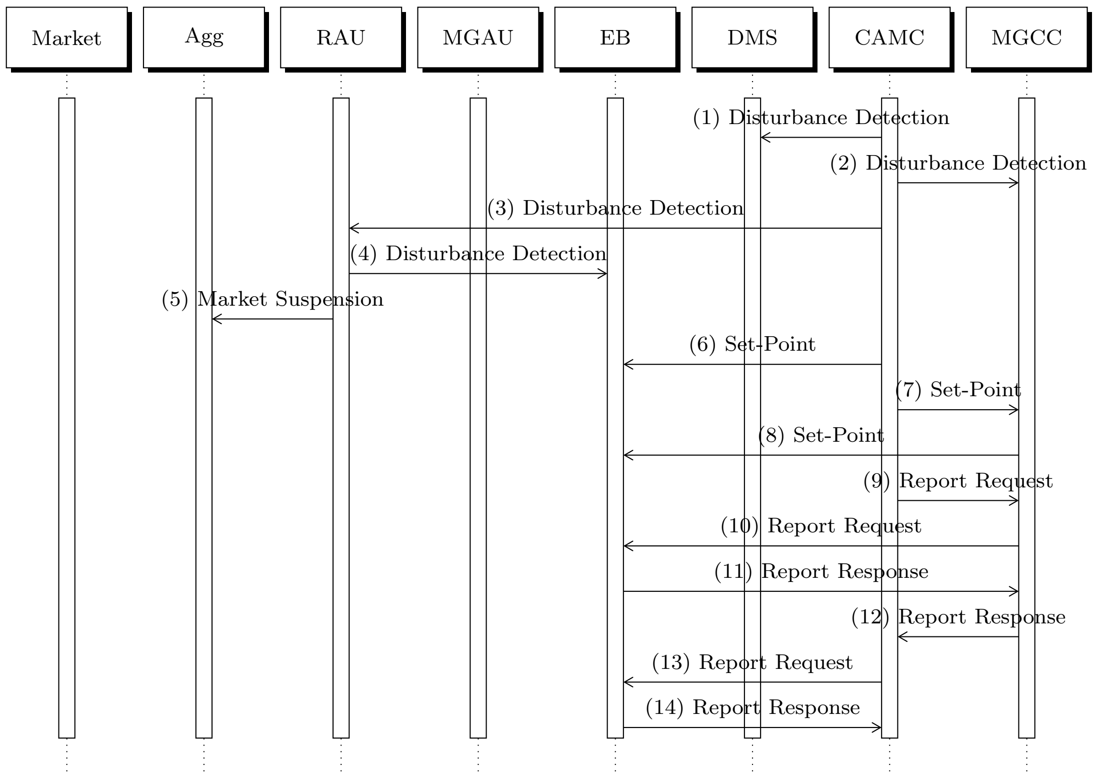



Figure 3.6: Emergency Operation State

6. A set-point is issued by the CAMC to target MV EBs to deal with the disturbance, via the RAU;

7. The CAMC issues a set-point to target MGCCs to handle the disturbance;

8. Each MGCC will assess the requested set-points from CAMC and, after running a local control algorithm, will issue set-points to the LV EBs under its supervision;

9. The CAMC issues a report request to involved MGCCs to assess the state of the system after the set-point exchange process is disseminated;

10. The MGCC in turn issues a report request to the LV EBs under its supervision to update the information to report back to the CAMC;

11. The target LV EBs report back to the managing MGCC;

12. The target MGCCs report back to the CAMC issuing the report request;

13. The CAMC issues a similar report request to the MV EBs under its supervision;

14. The contacted MV EBs report back to the CAMC and a new set-point exchange sequence can be initiated to ensure the necessary actions towards the restoration of the normal operation state.

## 3.6 Segmentation of Communications and Electric Networks

In Chapter 2 different architectural models were presented, which introduced a general overview of expected segmentation of the communications networks according to different parts or domains of the electric power system namely generation, transmission, distribution and customer. The wide variety and different interpretations regarding the functionalities of communications networks associated with specific segments of the electrical system induce a complex and very demanding communications infrastructure that must meet the requirements of smart grid applications.

Despite the major changes by the introduction of SGs, mainly at the distribution level, smaller changes are expected in other segments. The transmission segment has primarily to deal with the increase of data coming from the distribution grids, where typically limited information was retrieved. The communications infrastructure at this level is matured and sophisticated. It relies on fiber optics, or other broadband solutions, with very high bandwidth, reduced latency and very high reliability indices, making it a highly controlled environment. In the case of bulk generation, the promoter that explores the operation of large generators, like wind parks, is generally the responsible entity for the electric interconnection with the transmission grid. It is also responsible for the internal communications network for the control of generating devices and for the interconnection with the TSO communications infrastructure. In the customer segment, the communications within premises are a responsibility of the customer and the interconnection with the distribution grid from an electric and communications perspective is usually a responsibility of the DSO.

The main changes introduced in SGs will be in the distribution segment, with significant changes not only in terms of electric behavior (like different power flows and protective schemes to be considered, just to mention a few), with the introduction of distributed generation devices requiring active control and management systems, and in terms of communications to support the necessary data exchange required by advanced control strategies described previously.

The different communications networks envisaged for the upcoming distribution grids can be further segmented, considering functional reasons but geographical, administrative, physical or logical criteria can also be taken into account, since they can have a significant impact on the target technologies and solutions. However, the boundaries between such networks may not be clear, since in some cases they may share a common infrastructure. Furthermore, there is also the challenge in integrating interworking systems that can have different functionalities, which is the case of communications and electric power systems. Even when considering communications systems alone, interworking means for example that depending on the devices and applications to be supported different communication protocols have to be considered.

The last-mile concept aggregates both electric and communications networks and the previous discussion of using shared or separate communications infrastructures, introduced in the logic model, is basically a matter of the business model used to explore the different opportunities and challenges of SGs in this segment. The main technology alternatives in terms communications for this segment, either considering separate of shared infrastructures, were covered in the previous chapter. In the access or last-mile segment the distinction between different networks (according to the type of devices they interconnect or the applications they support) may be enforced at the physical level, by using separate infrastructures (possibly of different technologies), or by a logical separation over a shared infrastructure.

## 3.7 Summary and Main Conclusions

This chapter introduced a logic model to cope with the expected evolution of the smart grid paradigm, especially in what concerns the electric distribution segment, involving the main domains: technical, market and customer. This model accounts for two time horizons in the deployment of novel functionalities of the SG. It is based on an operational model that establishes the major states upon which the electric system is likely to operate and interconnects the technical and market operation.

Information flows were specified and use cases were presented to illustrate them and provide a basis for defining more complex scenarios with more detailed information exchange between entities. An integrated approach between the technical and market operation was assumed. Simplified market negotiation procedures and technical control actions were depicted alongside with the respective state transitions.

# Chapter 4

# Control and Communications in Distribution Grids

## 4.1 Introduction

There is a current debate on whether electric utilities should design and implement their own private networks or use public networks to setup a communications infrastructure capable of dealing with the data exchange that is expected to occur within the last-mile segment. There is a concern about the use of public network services due to a possible mismatch between the requirements that electric system operators envisage for the smart grid applications, which are derived from their typical operational values, and QoS guarantees that telecommunications operators commonly provide within their operational scenarios.

As referred to in the previous chapter there is a wide variety of smart grid applications, which do not require a direct interaction with the electric grid operation. On one hand market related applications can make use of public networks managed by telecommunications operators to support the necessary exchange of information that typically has less stringent requirements, even when intra-day market negotiation are required. On the other hand technical operation applications can rely on private networks typically designed and operated by electric system operators, where sensible requirements have to be met and heterogeneous communications segments may have to be considered. It may also happen that for certain field applications service provision by telecom operators is simply not available.

The advantage of having a network used only for applications related with technical operation, which does not share data traffic with other applications, is recognized by electric system operators. Furthermore there is a general conviction that in this way system operators have a better control over the communications networks in order to meet the necessary QoS requirements to support different operation control schemes. Data that is not directly used in the system operation can be exchanged through public networks and thus contribute towards the unburden of private networks. Hence, data related traffic volumes and respective patterns have to be considered according to each application and supporting communications network solution.

The logical model presented in the previous chapter established that grid operation information should be exchanged using a private network, typically owned and operated by the system operator, and that conversely market information could be exchanged through a public network. This allows currently available technologies to be considered for supporting the information exchange for the operation of the distribution networks, namely through the use of hierarchical control structures associated with microgrids and multi-microgrids. The current main alternatives envisaged to support last-mile communications are PLC and wireless multi-hop and the previously proposed data segregation makes way for the effective use of these technologies either as alternative or as complementary.

The use of private networks tailored to deal with control applications envisaged for distribution grids can potentially contribute to mitigate the uncertainty introduced by communications systems in general and their consequences in the aforementioned control schemes.

In this chapter different aspects of communications within distribution networks are discussed, namely in the last-mile segment where different technologies and approaches can be taken to support control strategies like microgrids and multi-microgrids. Section 4.2 analyzes the impact that the uncertainty introduced by communications can have in hierarchical control structures like those described in Chapter 2. A control algorithm capable of responding to emergency scenarios using a hierarchic structure is presented. The integration and impact assessment of communications systems is performed through configurable delays and loss ratios based on probabilistic rules. They allow evaluating the performance of the control system when in the presence of uncertainty and to explore the advantages of local distributed control schemes along with centralized control approaches.

The geographic context of Portuguese distribution grids is approached in section 4.3, considering both LV and MV distribution feeders. Relevant information is extracted from the available feeder data to help in characterizing the last-mile segment, upon which communications systems are expected to be deployed. A classification of feeders is established and a set of statistical tests are conducted over the extracted feeder samples, with the purpose of investigating candidate probability distributions capable of accurately representing the distance between potentially communicating node, which is dependent to each type of feeder. Using random number generators associated with these PDFs scenarios with different spatial positioning of such nodes can be generated as a form of creating the necessary variability to explore and evaluate the use of WMNs in Portuguese distribution grids.

In section 4.4 WiFIX is presented as a potential wireless multi-hop technology to be explored in the context of the last-mile communications, ensuring the necessary connectivity between potentially communicating nodes of both MV and LV distribution networks. A scheduling algorithm based on polling is used as a simple control mechanism and its performance is evaluated under the light of the uncertainty associated with delays and losses. The use of wireless solutions for the last-mile segment is regarded, in the scope of this thesis, as a complementary solution to PLC.

This technological cooperation between these two solutions can be seen as particularly interesting, since there is a recognized difficulty in using PLC technologies in the last-mile segment. Conversely there are challenges in ensuring that wireless communications are able to work properly both indoors and outdoors scenarios. The IEEE has recently released the IEEE 1901 as a BPL standard that targets connectivity both inside the building and in the outside within a short vicinity. Given the importance of such a technology in ensuring the necessary connectivity with the end customers a detailed study of the physical layer (PHY) of the IEEE 1901 is presented in section 4.5, in particular the error correction coding mechanism defined by the standard.

The section 4.6.3 is dedicated to the laboratory implementation and validation of some of the aspects discussed in the previous sections, namely the uncertainty of communications systems in the operation of a real microgrid system. It is intended to demonstrate the impact of the hierarchical control architecture previously mentioned in a near-real environment, when different control strategies are considered.

The final section presents a summary and an overall vision of the described methodologies in this chapter and points out some preliminary results that will be further evaluated and discussed in the following chapter.

## 4.2 Control and Communications in Multi-Microgrids

The different control schemes envisaged for smart grids require a communications infrastructure to convey data, whether the approach is centralized or distributed. However, there is a degree of uncertainty associated with the communications system that can introduce delays or even provoke losses of information. These phenomena can have a significant impact on control strategies, especially in electric networks with limited resources capable of handling disturbances. This impact can be higher when the electric network is operating in emergency or near emergency state, where technical violations have occurred. They can be aggravated if an islanding process occurs that jeopardizes even further the network survival capability. The latter can be considered as an extreme scenario but it is precisely under these conditions that communications need to be evaluated. The operating conditions are hence more stringent and local control strategies play an important role when combined with centralized secondary control schemes. Control set-points have to be issued to implement corrective actions to help in dealing with disturbances. Communications also have an important role in advanced restoration procedures, like in the case of a black start, but in such cases communications have typically less demanding requirements.

This section presents the methodological aspects of the implementation of a control scheme based on a multi-microgrid structure that is able to incorporate the uncertainty aspects of communications and evaluate their impact on the system response, namely its capability to survive in the event of a severe disturbance.

### 4.2.1 Control Strategy

The control scheme presented here is based on an earlier hierarchical MMG control approach developed and described in detail in [36] from where all the mathematical models of generators and regulators and their respective implementation were derived. The author proposes an autonomous control mechanism based on a multi-microgrid operation where a set of predefined rules allows this system to respond to changes in operating conditions. Despite the recognized value of this control implementation there are a few shortcomings that make it not entirely suitable for including the effects of communications, which were considered only by connecting or disconnecting elements at specified times.

Although based on this isochronous implementation the system here proposed consists in a complete reformulation designed to include an enhanced optimization tool to ensure an improved system response. It is based on a faster and improved control algorithm that includes: a variable control time step that can be discriminated according to the state of operation (normal or emergency), allowing the use of an isochronous or non-isochronous control strategy; variable controllable portfolio with different operating conditions; a discrete load shedding mechanism that can be configured with a predefined load shed step per area (different steps at MV and LV) or specifically customized for each load, allowing several combinations of shedding steps per load or distribution network; a communications emulation block; an automatic data collection mechanism with predefined time step for the analysis of results; and a multiprocessing operation design to ensure fast simulation of a considerable amount of scenarios, for instance for Monte Carlo implementations.

This control system was implemented in different modules, which were developed to deal with specific tasks, such as data collection and formatting, optimization of system operation, data output and processing of results. The MV and LV grids composing a MMG were implemented in the version 4.3 of the Eurostag simulator. It allows a fast dynamic simulation of the entire electric network. This is a discrete event simulator designed to solve the mathematical formulation associated with the continuous dynamic behavior of the different components of an electric power system. Sequences of actions pertaining to a particular electric network can be defined, thus allowing a multitude of scenarios to be considered and evaluated. The fact that models for controllable generators and regulators were already developed for Eurostag also contributed to the decision of using this SW package.

There are however some considerations and assumptions underlying this implementation. These shaped the control solution presented in this section, which can be summarized as follows:

- Eurostag is able to execute time bounded segments of simulation, allowing intermediate updating of parameters, which means that a control sequence can be divided into segments and simulated in a discrete fashion;
- The LV network is considered under an aggregated model, meaning that lines and respective equipment are not considered/modeled;
- The system is considered to be in steady state prior to any disturbance;
- There is an ongoing periodic monitoring process that allows the disturbances to be detected;
- The multi-microgrid is periodically aware of the available generation and load requirements at each monitoring time step;
- The optimization process is run separately at the MV and LV level and it determines an optimal solution, if feasible, or the closest non-optimal feasible solution at a specific point of operation;
- Loads do not have a local control thus relying on a centralized scheme to implement shedding strategies;
- It is assumed for the scenarios under consideration that there is always enough power within the microgrid to sustain priority loads (which are not controllable nor subject to shedding) otherwise a system collapse is very likely to occur.

The control system behaves like an AGC for isolated systems using a proportional-integral (PI) controller. In this type of systems the main function of the AGC is to restore the frequency to its nominal value by means of proportional and integral control, which ensures that the frequency deviation (error) converges to zero in the steady state [30]. To this end the PI controller will output a power variation

($\Delta P$) subjected to an input frequency variation ($\Delta f$), according to its configurable internal parameters (gains). The PI controller block diagram is depicted in Fig. 4.1. Eq. 4.1 represents the PI controller equation that is implemented within the control algorithm, where: $K_c$ is the constant gain, also designated as power system area gain, which is proportional to the total controllable power of the system; $K_p$ and $K_i$ represent the proportional and integral gain of the PI controller, respectively. The tuning of parameters of the PI controller is usually done through experimentation and it is based on the quality of the overall system response. This however depends on the characterization of the system under control (often referred to as the plant), which in most cases is very complex to model accurately. Moreover, the system is likely to change due to the stochastic behavior of some components and ultimately due to the impact that communications can have in the system response. Hence the optimal tuning of these parameters is considered to be outside the scope of this work.

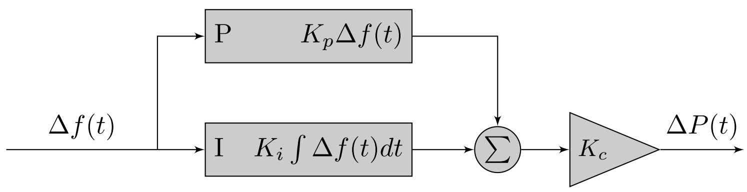



Figure 4.1: PI block diagram

$$\Delta P(t) = K_c \left( K_p \Delta f(t) + K_i \int \Delta f(t) dt \right) \tag{4.1}$$

The controller reacts to a frequency deviation, which in an isolated system that typically has limited robustness is caused by a power unbalancing event, outputting the necessary power variation to correct the deviation. This power variation intends to balance the system by re-matching the available generation with the existing load. The objective of this control action is to eliminate the frequency error based on the requested power variation; however, its scope should be limited to a power variation interval, to prevent a continuous secondary action allowing the available primary control to take over in between. This threshold prevents extemporaneous action of the secondary control, meaning that only outside a deadband will any actions take place. The overall control flow of the scheme here proposed can be found in Fig. 4.2.

The control algorithm consists in a periodic process that is executed in each sample time, $T_s$, in which the multi-microgrid is inspected and according to the operating state a centralized control process may be initiated. The sample time can be variable, allowing a higher sample frequency when a disturbance is detected and a more relaxed sample frequency when the system is operating under normal conditions or when the effect of the disturbance is eliminated. Hence, in each of these time periods the control algorithm starts by determining the system current frequency error and the respective frequency integral error, which can be obtained directly from the Eurostag output variables. Then power variation ($\Delta P$) is calculated using the PI control expression, representing the amount of power to be generated or curtailed to compensate the frequency variation. The required power variation is compared with a threshold/deadband establishing the decision to activate or not the secondary control. If the variation considered to be too small then the system leaves it to the primary control to react to the current operating

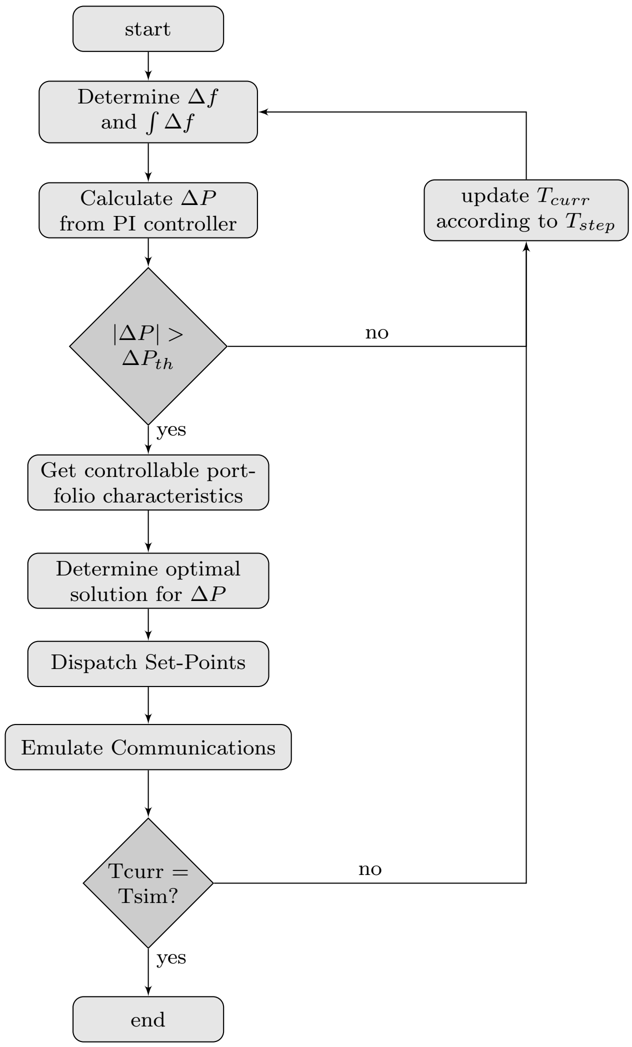



Figure 4.2: Control Algorithm Flowchart

conditions. Otherwise, the secondary control is activated, which starts by acquiring the controllable portfolio of the MMG. An optimal solution calculation, which will be described afterwards, is triggered. This optimization scheme is performed in a two-fold process, which starts by calculating the best solution at the MV level and afterwards the best solution for the LV level. The required set-points to implement the achieved solution are dispatched and a communications emulation module will introduce uncertainty to the information delivery process. This is also a two-fold process, starting with the MV set-point exchange and then the same process is repeated for the LV levels. The emulation of communications is specifically addressed in the following section.

The calculation of the optimal solution consists in a process where the required $\Delta P_{Total}$ variation is distributed over each of the available controllable portfolio elements, $\Delta P_i$, according to an associated dispatch costs list ensuring a solution with minimal cost. It is considered that costs are linearized at the point of operation and that they are able to incorporate starting and running costs.

The first approach used to solve this problem was based on a merit order scheme in which the total power variation starts to be assigned to cheaper elements according to their technical limits until the desired power variation is reached or until all element are fully dispatched yielding a minimal cost solution. This represents a fast and simple implementation if the feasible solutions space is continuous. However, a load shedding scheme was also implemented in which the load shed is performed in a step-wise fashion, which means that the feasible solutions space is no longer continuous, therefore introducing additional complexity to the merit order procedure. Nonetheless, if loads are considered to be always more expensive than generators within the controllable portfolio, representing a control element to be used only when there is no available generation to dispatch, a simplified merit order scheme can be implemented as depicted in Fig. 4.3.

This scheme assume that generators are always cheaper, which may be reasonable for instance if one considers load shedding as an event to avoid. As such, generators are progressively dispatched until $\Delta P_{Total}$ is reached. If the generators are not able to meet the required total power variation, making $\sum_i |\Delta P_{Gen_i}| < |\Delta P_{Total}|$, load power will have to be varied, with $\sum_j \Delta P_{load_j} = \Delta P_{Total} - \sum_i \Delta P_{Gen_i}$. The discrete nature of the shedding process within this control scheme will make it highly unlikely that the required value for $\sum_j \Delta P_{load_j}$ is exactly matched. This means that excess in load variation will have to be compensated by the previously assigned generators, in what can be called as reconciliatory power variation, defined as:

$$\Delta P_{Rec} = \Delta P_{Total} - \textstyle\sum_{i'} \Delta P_{Gen_{i'}} - \sum_{j'} \Delta P_{Load_{j'}}, \quad \text{for i'} \in [\text{assigned generators}] \text{ and j'} \in [\text{assigned loads}]$$

The rationale behind this merit order is fairly simple and this scheme is triggered in each control sample period. The overall objective is to generate a cost-effective solution to meet the target power variation ($\Delta P_{Total}$), for each observation period, based on the technical constraints of each participating element. Hence this scheme starts by initializing a control structure containing all the elements of the controllable portfolio to match the requested $\Delta P_{Total}$. In order to determine the solution with the lowest cost, all controllable elements, either generators or loads, are sorted according to their running costs. Since generators are considered to always be cheaper than loads their allowable power variation is progressively assigned as part of the solution in the first place. The amount of power varied by the sequential composition of the solution is evaluated and if the target power variation is reached the control sequence is deemed as concluded for the sample time. Otherwise, power variation of generators will keep being assigned to the solution until they are all assigned. The next step consists in assigning load power variation progressively to the solution until the target $\Delta P_{Total}$ is reached or exceeded. As previously mentioned the discrete load power variation can lead to an excess in terms of varied power and if this happens a reconciliatory $\Delta P_{Rec}$ needs to be calculated to match the initial target. This will require that the generators initially assigned to the solution must conversely vary the necessary amount of power to ensure that $\Delta P_{Total}$ is matched. This implies that these generators will have to be processed from the more expensive to the cheapest in order to ensure a minimal cost solution. It should be noted however that the target $\Delta P_{Total}$ may not be reached as it may represent a non-feasible solution in a specific control time sample period; however, when the merit order is finished, the closest solution with minimal cost is found.

As it was mentioned the previous merit order approach assumes that the power variation from generators represents the cheapest contribution to the solution composition. The expected presence of flexible loads in distribution grids whose owners are willing to participate in providing system services to the

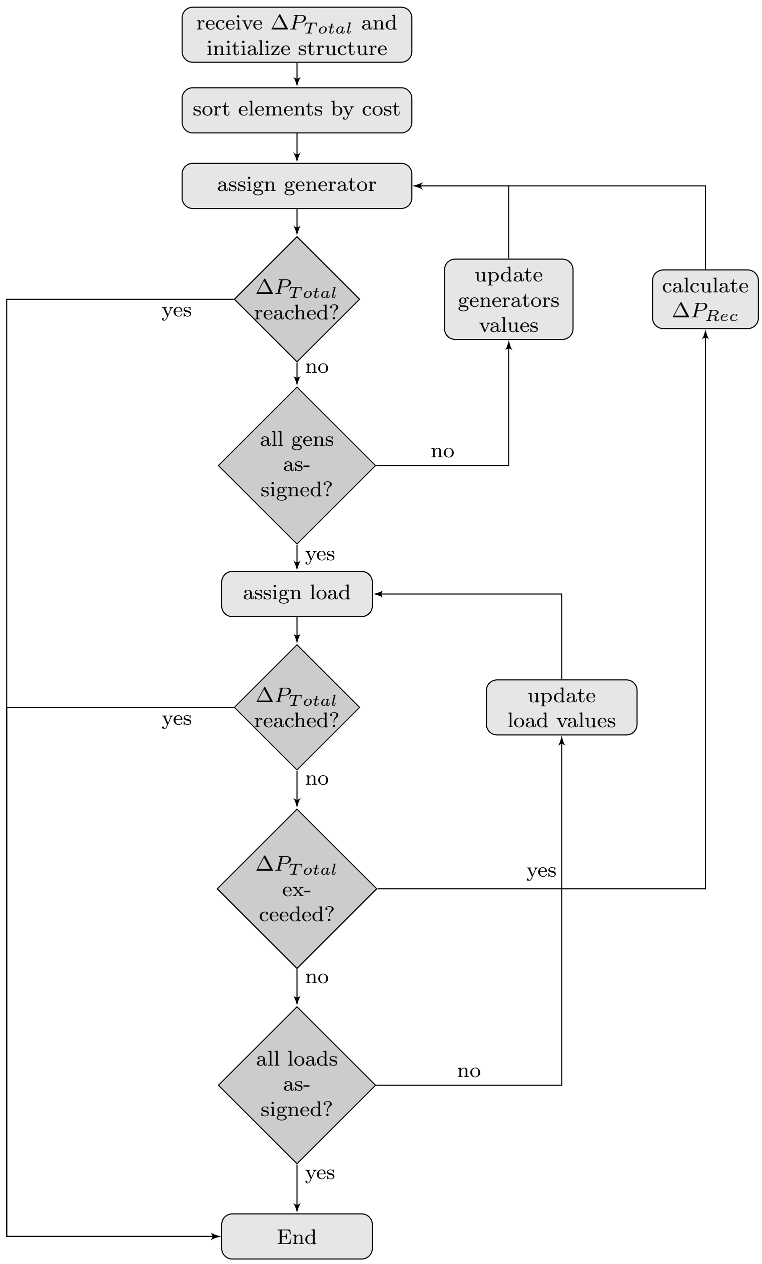



Figure 4.3: Simplified Merit Order Sequence

DSO may lead to a shedding event to be considered as a possible event with cheaper operational costs. This means that the sorted elements of the controllable portfolio can indiscriminately contain generators and loads. A modified merit order scheme is presented in Fig. 4.4.

In this version of the merit order the major change is processing of all sorted elements progressively whether they are generators or loads. Given the already mentioned discrete nature of the load shedding process, the excess in $\Delta P_{Total}$ only occurs when loads are being processed, meaning that a reconciliatory process needs to be carried out as depicted in the lower left side. As in the previous case, it is possible that

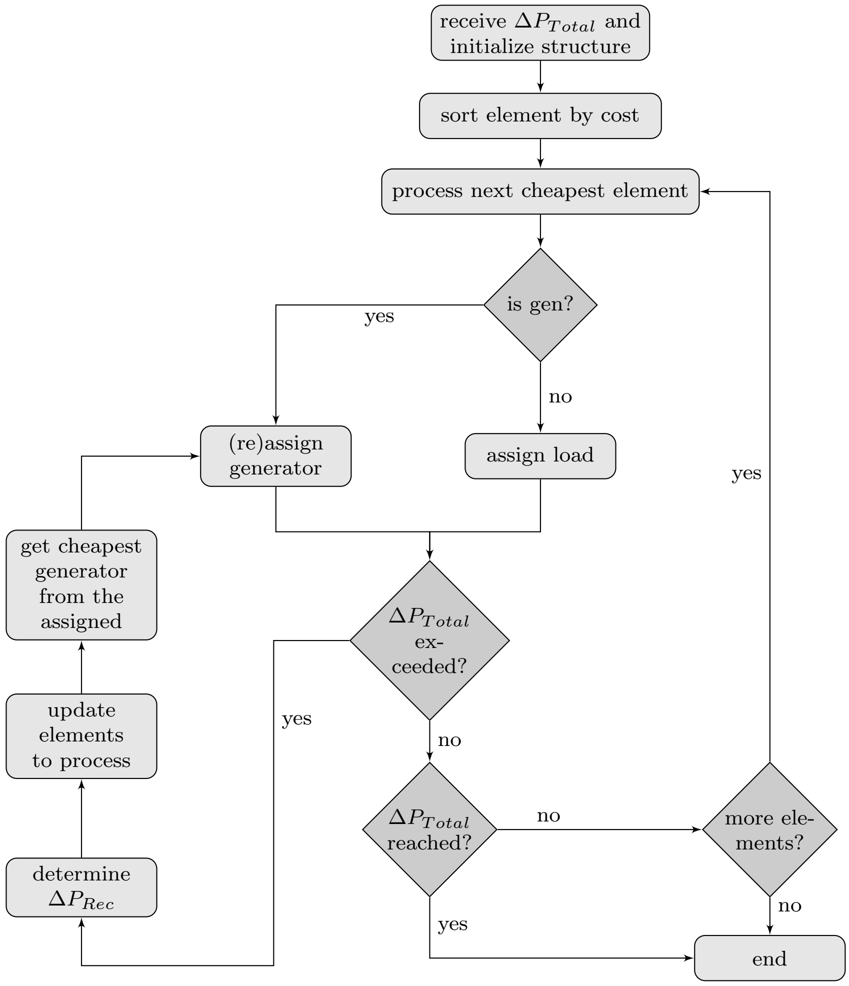



Figure 4.4: Enhanced Merit Order Sequence

the target $\Delta P_{Total}$ is not reached, being the closest cheap solution assigned by this assignment process.

Although the merit order approach can deem a solution in a simple manner, the introduction of further restrictions makes this approach increasingly complex and its adaptation cumbersome. A particular example of such complexity can be found in the use of non-linearized and time varying costs at the point of operation, which can yield a very intricate merit-order. This led to the consideration of a different solution to address this control scheme that allowed the introduction of new operating condition in a more flexible manner. The particular characteristics of Linear Programming (LP) formulation allow restrictions to be formulated independently of the algorithm execution, making it a suitable and convenient tool to deal with this sort of problems.

Generically, the problem associated with this control scheme can be described as a minimization problem where the objective is to minimize the overall cost of a feasible solution. A particular case of LP needs to be considered due to the discrete nature of the load shedding process, which is designated as Mixed Integer Linear Programming (MILP) formulation. A MILP inherently represents a difficult problem to be solved, NP-hard, which makes use of relaxation of constraints technique that allow the use of traditional LP solving mechanism.

The MILP problem formulation associated with the multi-microgrid control structure can be described by Eq. 4.2 that runs at MV multi-microgrid level and at each of the LV microgrids. The formulation under a MILP is very convenient since it allows restrictions to be added more easily. For example, it is possible to lock the shedding mechanism without allowing load re-connection while the disturbance is in effect just by truncating the lower bound of loads: $lb_j = 0, \forall j$. Another characteristic that can be associated is a variable cost function which may include for example a start-up cost.

Since one of the constraints is not an inequality it is necessary to introduce slacks to convert this formulation into the augmented form. The implementation of the MILP was performed through the PuLP module[1] for Python, which allows a formulation like the one presented earlier without the explicit conversion of the equality constraint. It offers an interface that, using Python core syntax, allows the formulation of LP problems and the use of external solvers. In this case GLPK[2], which is a callable library written in C freely available under a GPL license, was the selected solver. PuLP allows also a friendly printout of the LP formulation and provides an easy access to the achieved solution.

$$
\begin{aligned}
&\text{min z} = \sum_{i=1}^{m} c_i x_i + \sum_{j=1}^{n} d_j \Delta P_{s_j}\ y_j \text{ ,with } \Delta P_{s_j} = \frac{\Delta P_{Total_j}}{s_j} \\
&\text{subject to: } \sum_{i=1}^{m} x_i + \sum_{j=1}^{n} \Delta P_{s_j} y_j = min\left( |\Delta P_{Total}|; |\sum_{i=1}^{m} x_i + \sum_{j=1}^{n} \Delta P_{s_j} y_j| \right) \\
&\qquad |\Delta P_{Total}| > \Delta P_{threshold} \\
&\qquad \text{lb}_i \le x_i \le \text{ub}_i \\
&\qquad \text{lb}_j \le y_j \le \text{ub}_j \\
&\qquad x_i \in \mathbb{R} \\
&\qquad y_j \in \mathbb{N} \\
&\text{where:} \\
&\qquad c_i : \text{cost per unit of varied power of generator } i \\
&\qquad x_i : \text{amount of varied power to assign to generator } i \\
&\qquad m : \text{total number of controllable generators} \\
&\qquad lb_i : \text{allowable lower bound of power variation of generator } i \\
&\qquad ub_i : \text{allowable upper bound of power variation of generator } i \\
&\qquad d_j : \text{cost per unit of varied power of load } j \\
&\qquad y_j : \text{numberof varied steps of load } j \\
&\qquad n : \text{total number of controllable loads} \\
&\qquad lb_j : \text{allowable lower bound of step variation of load } j \\
&\qquad ub_j : \text{allowable upper bound of step variation of load } j \\
&\qquad s_j : \text{total number of steps for each load } j
\end{aligned}
\tag{4.2}
$$

[1] Available at: http://code.google.com/p/pulp-or/
[2] Available at: http://www.gnu.org/software/glpk/glpk.html

### 4.2.2 Uncertainty of Communications

The impact that communications can have on the information exchange process underlying a control scheme can be summarized in terms of global delays and losses. The overall delay concept is used as an aggregated metric and can be regarded as a sum of components that contributes to it, such as:

- The propagation in the communications medium;
- The processing time in nodes, which includes the transitions/conversions of communications protocol layers;
- Retransmissions due to failures;
- Transmission times on each hop along the path (due to the store and forward) that depend on the packet size and transmission rate.

Similarly, the loss concept can also aggregate globally different types of events that determine that a loss of information has occurred in the data path, like:

- Loss due to adverse propagation conditions or impairments in the communications channel; Recovery strategies may be used but losses may be permanent or still occur after a predefined number of retransmissions;
- Information at the receiving end was correctly interpreted but it is not valid;
- Data discarded at the receiving end due to expiration mechanism (e.g., timeout).

In order to evaluate the impact of communications in the previously described control scheme it became necessary to introduce uncertainty to the set-point exchange mechanism. An initial attempt to incorporate some characteristics of the communications systems was performed in [36] by associating a constant delay to the set-points exchanged within a control scheme. This results on a purely deterministic system where fixed delays are added to the dispatched actions issued by the control scheme, which are associated with a sequence of events to be processed by a dynamic simulation tool, like Eurostag. Hence a probabilistic process was introduced in the previously described control scheme in order to give more realism to the data exchange process and also to evaluate the impact on the overall system response due to uncertainties introduced in the set-point exchange mechanism, including delays and losses of information.

Different strategies can be used to recover from the errors introduced by the presence of delays and losses in the communications infrastructure that include end-to-end recovery (TCP/UDP) and hop-by-hop recovery in the communications path. However, it was considered that losses, when occurring, are permanent and no retransmissions are triggered creating an unfavorable scenario for the control scheme to handle.

The integration of the delay variation in the control scheme was introduced using a random number generator based on a normal distribution according to previously specified mean and standard deviation values. The well-known Probability Density Function (PDF) of the normal distribution is presented in the following expression:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}, \quad \text{for } \sigma > 0 \text{ and } -\infty < \mu < +\infty \tag{4.3}$$

Once the control algorithm has calculated the required set-points to be issued a delay value generated based on a normal distribution was added to the sequence of events pertaining to those set-points. It should be noted that delays in the control structure are cumulative meaning that if the CAMC issues a control set-point to a microgrid a delay is associated with this set-point exchange and then a new delay is associated again with the set-points issued by the MGCC to the controllable portfolio elements, which accumulates with the initial delay.

The losses in the data exchanged between the control management entities were introduced through a drawing mechanism. After knowing the number of targets to which set-points have to be sent, within the control action, a finite number of failures were randomly generated and indiscriminately assigned to each of these targets. This mechanism is based on the binomial distribution, which in turn is based on a Bernoulli process where a sequence of independently and identical Bernoulli trials are considered. Bernoulli trials are referred to as random experiments where only a binary result is possible: success or failure. The binomial distribution is defined by the PDF:

$$f(k;n,p) = \begin{cases} \binom{n}{k} p^k (1-p)^{n-k} & \text{, where } k = [0,1,2,...,n] \text{ and } \binom{n}{k} = \frac{n!}{k!(n-k)} \\ 0 & \text{, otherwise} \end{cases} \tag{4.4}$$

Hence, the loss mechanism is based on a random number generator that uses a binomial distribution to generate $k$ failures out of possible $n$ according to a probability of error $p$. Afterwards, a random number generator is used to assign the $k$ losses to the available $n$ targets. Similarly to the delay implementation, the losses occurred at the MV level have direct impact on the LV MGs, which means that no secondary control set-points will be issued within the affected MG.

### 4.2.3 Characteristics of the Integrated Control Tool

A control tool was designed to flexibly evaluate a centralized control scheme, based on a multi-microgrid structure, while accounting for uncertainties in the information exchange process which are likely to be introduced by communications systems. This tool makes use of a MILP implementation in order to establish the criteria to be used by the hierarchical control that at each sample time, $T_s$, decides the set-points to be exchanged among the different participants.

This tool makes use of a list of the available generators and loads inside the multi-microgrid, which can be configured as either controllable or non-controllable, the latter meaning that they have no role in the secondary control. Each participating element, either at the MV level or inside a microgrid, can be configured with allowable minimum and maximum active power, starting and running costs and locking mechanisms to prevent the same element to be assigned as part of a solution each $T_s$ time the system is evaluated.

The emulation of the communications systems is performed through the high level definition of delays and losses that can be established for each participating element or to groups, for example the case of a microgrid where the same typical values of delay and losses are applicable. A Monte Carlo (M-C) implementation is available to evaluate the uncertainty probabilistic formulation of the information exchange mechanism. This allows obtaining numerical results from a finite number of simulation runs in order to have a coherent analysis over the different scenarios created by the use of random number generators. It is possible to establish either a fixed number of simulation runs or to define a stopping criterion based on an allowable small deviation between the defined probabilistic parameters and the average values achieved after a finite number of simulations. The M-C system was designed to make use of parallel computing capabilities to increase the efficiency of the simulation platform and thus reduce the computation time.

On a final note it should be emphasized that despite the efforts in implementing a fast control structure, an unavoidable bottleneck was present. The mode of operation of the Eurostag simulator, in the 4.3 version used in this section, does not favor a synchronized action with an external module. By nature, the implemented control scheme requires that the dynamic simulation tool is kept in a pause state while the algorithms are run and different parameters are updated. This feature is not present in Eurostag and the only alternative was to run time bounded dynamic simulation segments, which results in a set of execution calls to the Eurostag modules. This has a considerable impact on the memory allocation and executions times and it becomes more clear when the number of calls is increased, for instance due to a smaller $T_s$. The use of parallel computing strategies helps in minimizing this factor in M-C simulations. It is expected that the incorporation of this pause functionality in future versions of Eurostag will yield a significant increase in the control system performance.

## 4.3 Feeder Characterization

A key issue in approaching communications for SG applications is the identification of the geographical scope upon which communications networks should ensure the necessary connectivity among different distribution grid entities and devices. Hence, the diversity in geographical information of electric distribution networks is an important aspect to consider in the strategy to be adopted when selecting the most appropriate communications architecture and technologies. In fact, the IEEE 2030 standard [55] emphasizes the importance of context information, namely in terms of geographical data that allows a better characterization of the potential communications scenarios. In general, the current knowledge that utilities have regarding the distribution grid is limited and the modernization process introduced by SG is also being used by DSOs to enhance their awareness in terms of location and geographical distribution of the different components that are already installed and those to be installed. This allows a better characterization of their distribution networks.

This characterization addresses, among other aspects, the identification of the typical number of customers in distribution feeders, the serving secondary substation to which they are connected to, and the involved distances. Since each customer is considered as a potential active participant in the SG, requiring a bidirectional flow of electricity and data, this information will allow electric grid stakeholders to better plan and operate the distribution network. With this purpose in mind, a classification and detailed characterization of distribution feeders is presented in this section. This work was performed in cooperation with the Portuguese DSO, EDPD[3], with the identification of the potential communicating nodes and the associated distances, which includes the electric cable distances and the linear distances. A specific tool, based on graphs, was developed to process the supplied feeder data with the purpose of enabling a graphical representation, in a schematic or in a tree, of the different component of each electric

[3]EDPD - Energias de Portugal - Distribuição - www.edpdistribuicao.pt

network. Both LV and MV distribution networks were considered and the representation resulting from the evaluation of the associated data is presented in Appendix D.

From the evaluation conducted over the geographical information of the different feeders it was considered the possibility of generating random scenarios of distribution networks based on the available samples. The objective was to create diversity in node positioning having in mind the characteristics associated with different samples. One particular aspect to consider is the distance between potentially communicating nodes. Since these nodes are likely to be part of the control structures approached in the previous section, the randomly generated scenarios can allow assessment of a communications infrastructure for both LV and MV distribution networks.

Hence, a set of probability distributions was considered as capable of representing the node placement, considering different scenarios. The use of random number generators, based on each PDF considered for each type of scenario, allows the introduction of variability in node position thus creating the aforementioned diversity. Empirically, histograms of the data samples were initially used to allow an approximate perception of the data distribution and thus provide an indication of the potential candidate PDFs that could be used to accurately represent the available data. Despite the usefulness of histograms in the characterization of data, one must bear in mind that there are well-known shortcomings, namely the inherent distortion associated with the specific rule used to define the absolute or relative data frequency in each class/bin. According to the number of bins and their width (discrete intervals) over which data frequencies are considered, the histograms can vary significantly. Due to this variation the selection of bins can be performed using empirical rules like the square root, Sturges, Freedman–Diaconis among many others. The square-root was the preferred rule since it allowed a balanced representation of the data.

The evaluation of candidate probability distributions as accurate representations of sample data is called a Goodness of Fit (GoF) procedure, where statistical tests of hypothesis are used to decide whether to accept or not a specific PDF. As stated in [119] a GoF problem consists in testing a sample against the hypothesis that the data can be associated with a particular PDF. This means that in GoF tests the null hypothesis ($H_0$), if true, states that the distribution under evaluation is fit to represent the sample data under analysis. Among the typical tests are the chi-square, the Kolmogorov-Smirnov (K-S) and the Anderson-Darling (A-D). It should be noted that prior to the execution of any of these tests an estimate of the parameters of each candidate distribution must be performed. A maximum likelihood estimation is performed and the estimated parameters can allow the use of random generators based on that distribution to create several scenarios.

Despite the value and usefulness of the goodness of fit tests, a decision is to be taken, which in this case means to either reject or not a particular PDF as an accurate representation of the data under consideration. This type of decision, based on complementary hypotheses ($H_0$ is true or $H_0$ is false), can have two types of error: type I and II. The type I error occurs when $H_0$ is rejected when it is true, whereas the type II error occurs when $H_0$ is not rejected but it is false. The level of significance, $\alpha$, used in each of the hypothesis tests, can conversely affect both types of error. Given that the significance levels typically used in these types of tests are commonly 1% and 5% [120], these were used in all the conducted hypothesis tests. The significance level basically represents the probability of incurring in a type I error.

The chi-square non-parametric test is used due to its popularity in the hypothesis test, however it is necessary to take into account some assumptions and specificities of this test. As explained in the literature, for example in [121, 122] the chi-square test depends on the sample size, particularly the number of expected occurrences in each bin/class. Empirically, it is assumed that at least 5 elements are associated with each class in order to ensure a minimum accuracy of the test, which is the case of the considered data samples. Since this test depends on the considered bins, in terms of number and size, the results of this test can be affected by the aforementioned distortions in the histogram, which can make the test result to vary significantly.

The K-S is also a non-parametric test usually used to compare a sample with a probability distribution, also known as one-sample K-S test. It deems the distance of the Cumulative Distribution Function (CDF) of the sample and the CDF of the considered probability distribution. It is sensitive to both the location and shape of CDFs and thus it is sensitive to local and extreme deviations. In the K-S test the critical values do not depend on the distribution under evaluation. Besides normality tests, the K-S can be modified for testing other distributions, making it suitable for GoF procedures [123].

The A-D test serves a similar purpose and is regarded as a modification of the K-S. It is a test that puts more weight on the tails than the K-S test. The A-D test uses the parameters of the specific distribution under evaluation to determine the critical values, which have to be calculated for each distribution making the test more sensitive [124].

It should be noted that the GoF is used in the context of geographical characterization. It does not intend to find the probability distribution closest to the available data but rather find a set of candidates able to coherently fit the data variability. As such, despite the vast number of continuous distributions, the assessment was restricted to a set of continuous probability distributions that can be associated with the distance variable characteristics: Burr, exponential, gamma, log-normal, generalized Pareto and Weibull.

A more accurate graphical representation of the proximity of a data sample to a determined distribution can be achieved through the use of Quantile-Quantile Plots, commonly known as QQ plots. Typically in QQ plots if the points of the data sample quantiles and the points from a specific distribution quantiles fall on or near the $x = y$ line then there is an agreement between the theoretical and sample data distributions. The QQ-plots are also used in the data analysis conducted in the next chapter to allow an interpretation of the sample point pattern. The combination of the tests of hypothesis and QQ plots allow a more sensible analysis and deciding on the desired strategy in terms of representation of data.

## 4.4 Wireless Mesh Networks for Distribution Network

The difficulties in conveying data reliably and at high data rates in power line communications networks has raised some concerns regarding the ability of using the electric medium to exchange data. Hence the need to consider alternative technologies for electric distribution networks that fall within the last-mile segment. On one hand, the installation of another cabled network, based on a different technology, with the purpose of tackling the difficulties in PLC seems unfeasible given not only the associated cost but also the intensive labor and deployment time of such activities. On the other hand, the use of wireless technologies in electric power systems environment seems to be gaining attention due to their recognized advantages in supporting different applications that range from real-time, like protection systems, to non-real-time, like smart metering.

In particular, wireless multi-hop approaches have interesting features to be implemented in this scope and the inherently associated limitations that have been the topic of research in several areas (e.g. fairness, scheduling, congestion control, spatial reuse) in order to devise solutions to overcome them, as mentioned in Chapter 2. The use of wireless mesh networks, as extension of infrastructured networks, represents a suitable candidate for the last-mile communications segment of smart grids, where a convergence between infrastructure networks of both end consumers and system operator or market representatives is needed. In fact WMNs can be regarded both as an alternative and as a complementary solution to PLC since it is designed to be deployed in scenarios were other technologies are unfeasible or impractical.

This section approaches the use of WMNs in the scope of the last-mile segment, where the power feeder characterization presented previously will allow the generation of different scenarios that are likely to be found in electric distribution networks. In these scenarios the number of potential communicating nodes and the typical distances between them will be explored, thus allowing the evaluation of a particular WMN implementation based on WiFIX.

### 4.4.1 Generation of Scenarios

With this purpose in mind a generator of random trees was designed and implemented to allow the generation of different scenarios where potential communications nodes and their respective position is defined according to the intrinsic characteristics of each type of distribution feeder. The algorithm is represented in the flowchart of Fig. 4.5 and is based on a random node positioning scheme that uses a list of randomly generated distances between neighbor nodes. Nodes are placed in radial form, which means that according to each distance a new node is placed while guaranteeing that there is no other node closer. As such, areas for feasible placement of node need to be established, as it will be mentioned in the algorithm description. Nodes are positioned according to: a predefined radius limit; total number of nodes associated with each scenario; and the amount of different scenarios to be generated with similar characteristics.

In the algorithm flowchart, in Fig. 4.5, a list with random distances between neighbor nodes is initially created using a specific PDF, which is selected according to the desired type of scenario with parameters that have to be estimated *a priori*. A root node is defined and added as the first and central node in the overall list that will be composed of as many nodes as initially stipulated. A new node is defined and a value is retrieved from the random distance list. This new node will be place as a neighbor of a node already installed, which will be a candidate parent node, in a radius defined by the distance value. Feasible values of theta ($\theta$), in which no nodes other than the candidate parent exist, are calculated in order to determine the polar coordinates of the new node. This means that different areas for node placement will be tested using a predefined ($\theta$) step. If no feasible values are found for $\theta$ a recursive approach may be taken according to a resolution limit upon which no further evaluation is conducted. If the resolution threshold is exceeded then a different radial distance is considered from the random node distances list and new values for $\theta$ are again computed. If there is no radial distance for which a feasible $\theta$ can be found then a different parent candidate node is selected and the process it repeated again. When a feasible list of $\theta$ is found then a random $\theta$ value is selected form this list, the corresponding Cartesian

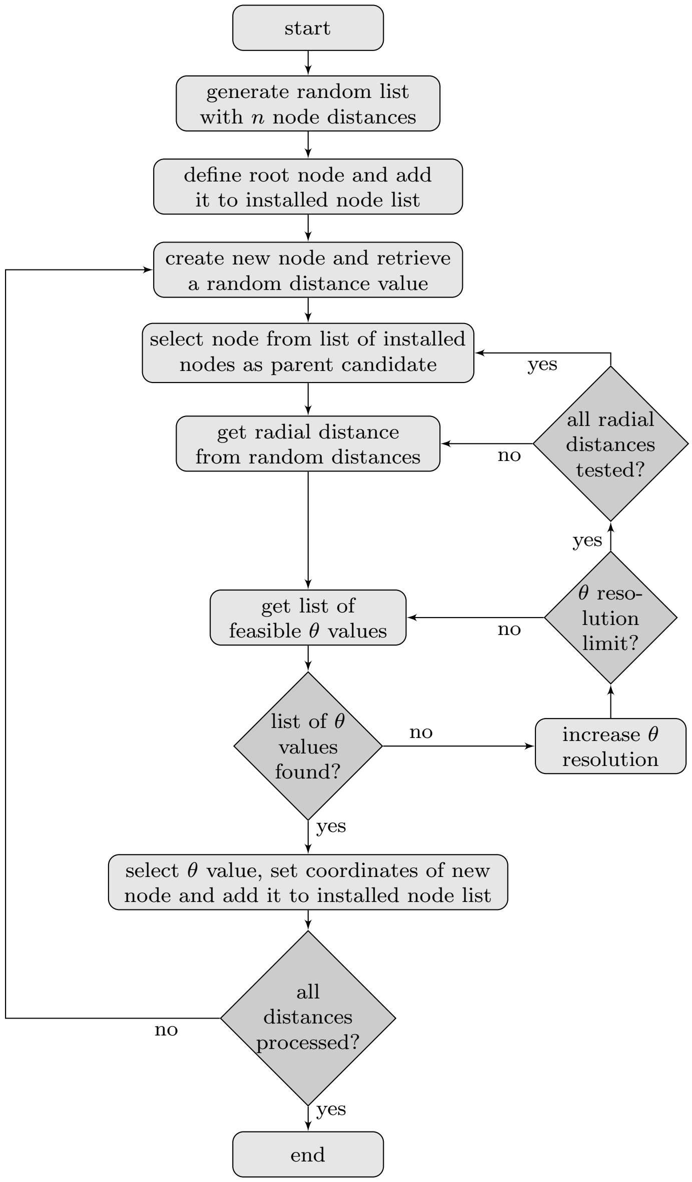



Figure 4.5: Random Tree Generation Algorithm Flowchart

coordinates are determined and the new node is added to the list of installed nodes. The scenario is completed when all distances are processed. A predefined number of scenarios will be used afterwards in the evaluation of the WiFIX implementation.

### 4.4.2 WiFIX Network Implementation

In project REIVE a specific implementation of the WiFIX algorithm proposed in [81] and [82] was adopted towards its implementation in the scope of smart grids targeting smart metering applications. As mentioned, one of the main advantages of WiFIX is the fact that it is implemented between layers 2 and 3 of the OSI model, which means that different technologies associated with the first two layers can be used to support this solution. The main objective is to understand its applicability in the context of the distribution networks as a support infrastructure for last-mile communications scenarios, considering control strategies like those approached in previous sections.

In [125] the advantages of a specific polling mechanism over CSMA/CA, designated as PACE, when compared to the typical CSMA/CA are presented over a new WiFIX version with backwards compatibility. PACE uses CSMA/CA as standard technology to deal with "residual" collisions namely from the control traffic that shares the same channel of the data traffic. By limiting data transmissions to a single mesh node at a time and by allowing each node to transmit a packet in each network-wide transmission round, PACE scheduling mechanism is able to solve the inefficiency and unfairness problems. The WiFIX implementation presented here is based on IEEE 802.11 and processes all incoming/outgoing packets. A polling scheduling mechanism is also proposed here over a modified implementation of WiFIX. The rationale for this decision is associated with the context of the last-mile communications segment of smart grids:

- Potentially communicating nodes in distribution grids are expected to exchange data mainly with a central controller to ensure that status information and control orders are implemented. As such, a logical tree topology using WiFIX over the physical network is compatible with the presence of chains terminating at a GW.

- Control schemes presented previously may not need a complete network transmission round, meaning that for a specific control action not all nodes have to participate. This favors the use of adaptable control sequences that can easily be implemented using polling schemes, which due to their simplicity and centralized approach can be dynamically changed in each network round.

- The selection of the GW node, as head of the scheduling mechanism for downstream traffic and polling sequence, can be associated with the node responsible for the control of a microgrid, or at a higher level of a multi-microgrid.

From the previous generation of scenarios, where potential communicating nodes are established according to specific types of distribution networks, it became necessary to implement an algorithm to deploy nodes associated with a WMN and to ensure the connectivity between all participating nodes. Hence, all nodes from the generated scenarios are also nodes of the WMN, but since the involved distances can potentially make some nodes unreachable, relay nodes may have to be added. The flowchart in Fig. 4.6 illustrates the algorithm that starts by loading the nodes from a specific scenario as nodes capable of generating data traffic. These are considered to be MAP nodes of the WiFIX network, like the GW node, which is identified and used as the reference node. The relay nodes are used only to extend the connectivity between MAPs and they only forward data, which means that they will not generate traffic.

An iterative process over the loaded nodes is performed, where paths towards the GW are established. The geographic distance to the GW is calculated and a list of candidate neighbor nodes, that are closer to the GW, is determined. If there are no closer nodes, then the closest neighbor is in fact the GW itself. Afterwards, the need for relays is evaluated based on the admissible radio distance to ensure coverage between consecutive hops, allowing the connectivity of the current node with its closest neighbor.

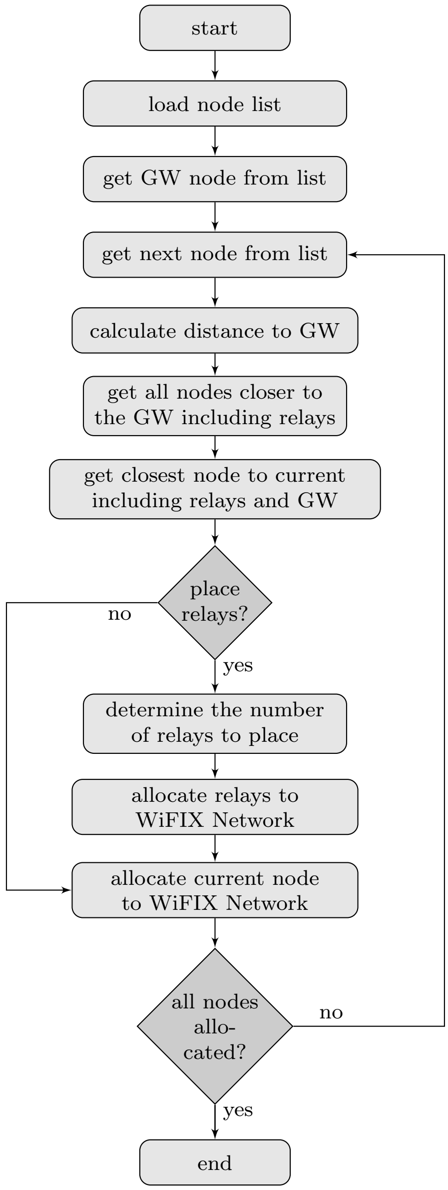



Figure 4.6: Node Placement of WiFIX Network Flowchart

If necessary, a minimum number of relays is calculated and placed, considering that the maximum hop is bounded to 80% of the established radio distance, thus allowing some safety margin in the implementation of the WiFIX network. The distance between relays that are used to extend the coverage is the same, meaning an equidistant strategy is employed for deploying relays between the current node and the closest neighbor, either a MAP or another relay. Afterwards, relays and current nodes are allocated to the WiFIX network structure. If relays are not necessary then only the current node is allocated. The node placement process is considered to be finished when all nodes are allocated.

This relay placement algorithm is simple and fast since it does not use any context information like distances, obstacles or the number MAP nodes to which connectivity with the GW needs to be established.

This solution is suitable for the purpose of evaluating the generated scenarios in a Monte Carlo scheme. However, this simplified approach may lead to the assignment of unnecessary relay nodes to ensure the overall connectivity inside the WiFIX network. This means that no optimization criterion was used since once again the purpose is to ensure a quick evaluation of a large number of potential scenarios. This optimization approach is usually taken in planning activities, where typically multi-criteria can be used, and where node placement restrictions, that depend on specific context information, need also to be accounted for.

A few changes had to be introduced to the original WiFIX implementation to deal with the context upon which these networks are expected to provide connectivity and the associated polling mechanism. Originally, in WiFIX, routes are not created before data is exchanged since the learning bridge process is used. As such, a virtual tunnel between two mesh nodes (parent and child) is created only after the parent node receives an explicit unicast message sent by the child. In this implementation the parent node then forwards this message to the GW thus allowing routes to all intermediate nodes to be established. The GW is able to know the entire network topology by means of a discovery process that is triggered in a warm-up stage, allowing at a later stage to initiate the polling scheme. Given that node density can vary significantly depending on the physical position of communicating nodes and the necessary relays, no limit was considered for the number of children each parent can support, as opposed to the previous implementations of WiFIX.

## 4.5 Power Line Communications for Distribution Grids

Historically, electric system operators have relied on dedicated communications systems to implement different types of applications that range from very stringent and very fast real-time protection systems up to more relaxed and non-critical remote metering applications. These are usually systems owned and managed by utilities and they are seldom implemented using third-party communications networks.

In this regard there is a convenience in the use of power line communications (PLC) as a medium to convey data since it provides a path between the utility operation center through its assets and equipment all the way to the end consumer that is an infrastructure already deployed. Furthermore, PLC represents a communications network that is the property of utilities and it is used typically as a private network. It is also an important tool used in the characterization of distribution networks, which are in general not well characterized mainly due to the prevalent philosophy of “fit-and-forget” that was followed, up until recently. Data connectivity can allow associating a consumer to the corresponding electric feeder in an automated fashion without having to incur in labor intensive activities, which given the associated costs could compromise the quality of such characterization.

The difficulties in conveying information over such a harsh media and current regulatory dispositions have been favoring the use of narrowband PLC solutions in the distribution network. The limitations of the first generation of PLC are well-known and the second generation promises to solve most of them, but it still relies on a limited bandwidth solution to provide an end-to-end communications infrastructure for distribution networks. The recent IEEE 1901 is set to bring the broadband PLC (BPL) technology outside the in-building environment, where it was initially designed to operate. Its physical layer (PHY) characteristics seem to make it suitable to support communications within buildings and near their vicinity.

Given propagation difficulties that are prone to be found in the last-mile segment, where the characteristics of the medium are likely to change constantly and abruptly it is not expected that BPL would be able to completely tackle these issues. Instead, this type of technology can be thought as a complementary solution to the wireless multi-hop network presented in the previous section, which was introduced as a solution capable of offering connectivity mainly outside the building environment. Since one of the main issues in designing a solution for the last-mile communications segment is precisely its heterogeneity, BPL can be thought as a potential way to allow conveying information from outside the building environment to the customer premises.

This rationale motivated the study of the IEEE 1901 as an alternative in allowing the information exchange between the indoor communications networks of customer and the outdoors communications solutions of the system operator. The importance in conveying information between the system operator and end-customers is crucial in order to allow their participation in the foreseeable smart grid service exchange model. As such, this section focuses on the exploration of the IEEE 1901 PHY layer, namely the error correction coding techniques that are used to ensure the necessary information resilience in an error prone media like PLC.

### 4.5.1 Simulation of the Physical Layer

The IEEE 1901 standard defines two physical layers using respectively an FFT and a wavelet approach along with a coexistence scheme, called Inter-System Protocol, to ensure interoperability with other PLC devices, namely ITU-T G.hn devices. Of particular interest is the FFT implementation that defines differentiated parameters for both in-home and access implementations. It is precisely the latter that will be explored given the scope of this thesis. The architecture of the FFT transceiver defined in the standard is fairly complex and contains particular aspects that are not relevant for the intended analysis, as such a simplified version was created. This version, presented in Fig. 4.7, disregards aspects related with HW implementation of transceiver signal handling like FFT operations, gain control, time synchronization, among others. The implementation of the TIA-1113 compatibility frame processing is disregarded, as well.

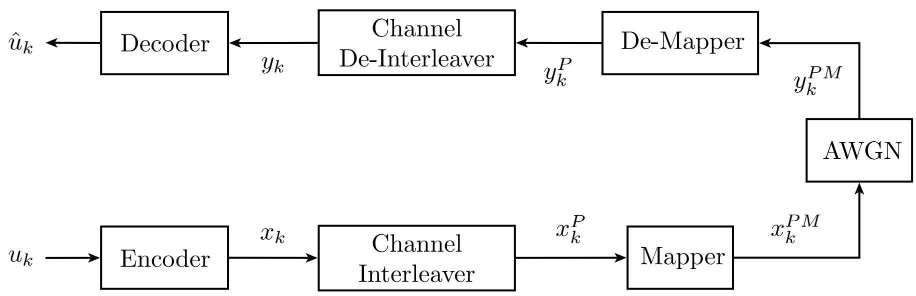



Figure 4.7: Simplified IEEE 1901 System Blocks

The standard defines different Physical Protocol Data Units (PPDU) that correspond to the actual data sent over the communications medium. The PPDUs can be compatible with TIA 1113 or 1901-compatible only and they can also carry or not payload data, respectively designated as short and long PPDUs. The standard defines a different Forward Error Correction (FEC) encoding mechanism respectively for frame control and payload bits. The frame control bits are encoded through a convolutional encoder, an interleaver and a diversity copier whereas the payload is encoded through a scrambler, a convolutional encoder and a channel interleaver. The convolutional encoder is a common block used in both cases and it will be explored in more detail later in this section. For simplicity, only the case of the payload encoding process is considered. This analysis remains of course valid for the frame control encoding scheme where minor adaptations are needed.

The communications mechanism associated with IEEE 1901 is well-known and it basically consists in an encoding scheme at the transmission phase, which allows soft-decoding techniques at the reception. This process intends to provide enhanced resilience to data exchanged in lossy medium, where regeneration techniques can be employed. This allows corrupted parts of the exchanged data to be corrected by the unaffected parts due to the correlation established in the encoding process. The simplified communications system considered here was designed to allow the study of the different components of the encoding and decoding processes.

A simplified simulation system of the IEEE 1901 PHY layer was implemented, using separate blocks as illustrated in Fig. 4.7, which were defined according to their specific purpose. This strategy allows the isolated testing of each component, and a detailed description of their implementation is presented below. Due to the recursive nature of this type of systems a special attention was given to the overall system performance. It should be noted that this type of implementation is not bounded by HW restrictions, however it incorporates some of them given their importance on the system performance as will be mentioned.

The encoder is responsible for the convolutional encoding process, which includes a FEC mechanism. The standard defines three types of code rates, specifically "1/2", "16/21" and "16/18", along with different Physical Blocks (PB), respectively PB16, PB136 and PB520 with the number defining each PB size in octets. Table 13-16 in [67] summarizes the allowable combinations of PB sizes and code rates.

The encoding architecture includes a convolution encoder and an interleaver. The first is also known as turbo convolutional encoder due to the decoding process usually associated, which will be addressed later in this section. The latter is specifically designed according to the data to be encoded: frame control or payload. If the information to encode concerns payload, an initial scrambler is used, as depicted in Fig 13-1 in [67]. For simplicity, only the payload encoding process is considered.

The convolutional encoder defined in the standard and depicted in Fig. 4.8 is composed of two parallel Recursive Systematic Convolutional (RSC) encoders. The RSC 1 generates the parity bits from the input sequence, whereas the RSC 2 generates the parity bits using an interleaved version of the input sequence. A puncturer is used to puncture the parity bits, meaning their exclusion from the final encoded sequence according to different puncturing patterns. This mechanism can allow a great diversity in terms of code rates but only the patterns defined by the standard are used.

These RSCs, often referred to as feedback encoders, are also designated as "2/3" encoders, which means that for each 2 bits of information a parity bit is generated and added to produce an encoded

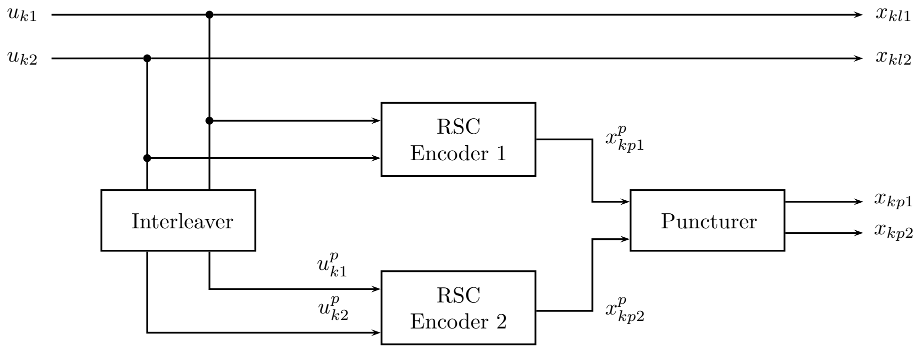



Figure 4.8: Encoding Architecture

sequence. The combination of these RSCs in parallel will yield a 2/4 encoder, since they are used to produce one parity bit each, meaning that for each 2 information bits 2 parity bits will be added apart from puncturing. This particular characteristic makes this encoder to be commonly designated as duobinary and it represents a particular case of the non-binary codes, with a recognized fair trade-off between the error correction capacity and the decoding complexity, as emphasized in [126].

When observed carefully each one of the RSC encoders represents in fact a feedback encoder with $\frac{k}{k+1}$ code rate. This is a well-known type of convolutional encoder, where a single parity bit is appended to the information sequence $k$. In [127] this type of encoders and the respective encoding specificities are approached in detail. A generic $\frac{k}{k+1}$ RSC encoder scheme was thus implemented, as depicted in Fig. 4.9, which according to the input configuration binary matrices, presented in Eq. 4.5 also in its generic form, is able assume a specific topology. This means that convolutional operations are activated or deactivated by these matrices, which are defined as follows [128]:

$$\mathbf{H} = \begin{bmatrix} h_m & h_{m-1} & ... & h_0 \end{bmatrix} \text{ and } \mathbf{G} = \begin{bmatrix} g_m^1 & g_{m-1}^1 & \cdots & g_0^1 \\ g_m^2 & g_{m-1}^2 & \cdots & g_0^2 \\ \vdots & \vdots & \ddots & \vdots \\ g_m^k & g_{m-1}^k & \cdots & g_0^k \end{bmatrix} \tag{4.5}$$

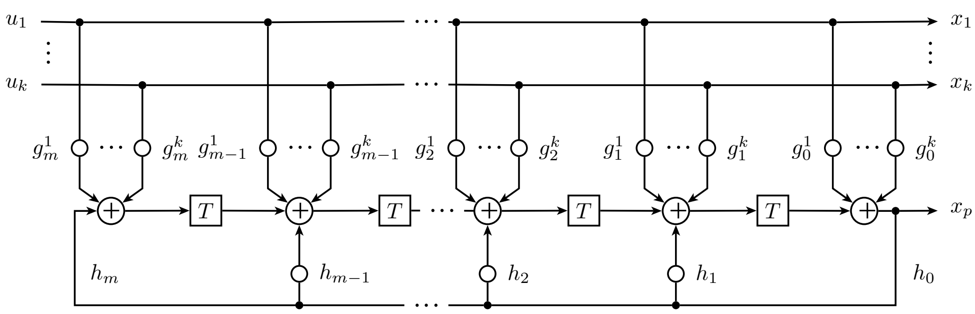



Figure 4.9: Generic RSC Encoder

If the matrices G and H are properly defined, the topology of the generic RSC encoder will be the same as the 2/3 RSC used in IEEE 1901, as illustrated in Fig. 4.10:

$$\mathbf{H} = \begin{bmatrix} 1 & 0 & 1 & 0 \end{bmatrix} \text{ and } \mathbf{G} = \begin{bmatrix} 1 & 1 & 0 & 0 \\ 1 & 1 & 1 & 1 \end{bmatrix}$$

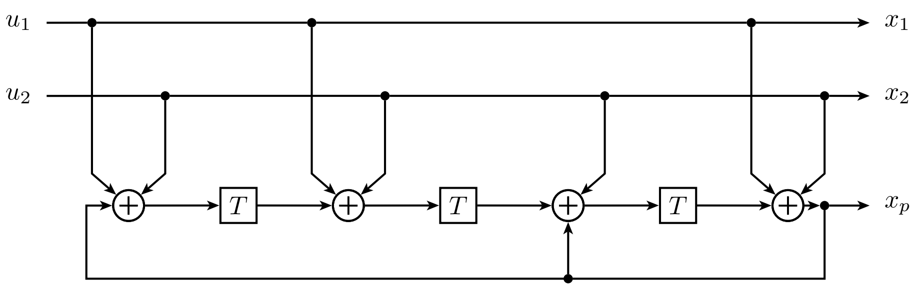



Figure 4.10: IEEE 1901 RSC Encoder

Like any other encoder, it is characterized by its constraint length $K$, which corresponds to the max number of elements of each row of matrix $\mathbf{G}$; its memory $M$, which defines the number of possible states of the encoder and generically the number of encoded bits, $n$, output by the encoder for each input information bits, $k$. Thus for this specific encoder the values of the parameters to consider are: $K = 4$, $M = 3$, $k = 2$, and $n = 3$.

The RSC encoder operation can be represented by a state diagram with a finite number of states and respective transitions. A trellis representation is presented in Fig. 4.11, which is a compact form of presenting the same information, when the number of states is small.

The trellis summarizes all the possible state transitions, triggered by different input sequences and the corresponding output sequences of the RSC encoder defined in IEEE 1901. The concatenation of this structure is used in the decoding process, when a path between the trellises needs to be estimated. Each trellis path represents an estimate of the corresponding input binary pairs that is performed using the receive sequence and typically a maximum likelihood estimation procedure.

The puncturer is responsible for the effective assignment of parity bits that will be used in the overall encoded sequence output from the convolutional encoder. It allows the use of different code rates other than the 1/2 "base code rate" stipulated by the encoder structure, as illustrated in Fig. 4.8. The puncturing patterns defined by the standard are responsible for the three different coding rates: 1/2, 16/21 and 16/18.

The encoder interleaver is responsible for interleaving the original sequence in a duobinary fashion, where parity bits are calculated in pairs for each pair of input bits. This binary based operation intends to interleave the coding pattern, in order to make the encoded sequence more resistant to errors. This interleaving process is based on an interleaving map, $I$, defined by $I(x) = [S(x \text{ mod } N) - (x \text{ div } N)N + L] \text{ mod } L$, for $x \in [0, 1, ..., L-1]$, where: $S$ is the interleaver seed table, which depends on the size of the physical block used in the FEC mechanism; $N$ is the length of the seed table; and $L$ is the interleaver length that corresponds to the number of bit pairs to be processed in the specific physical block size.

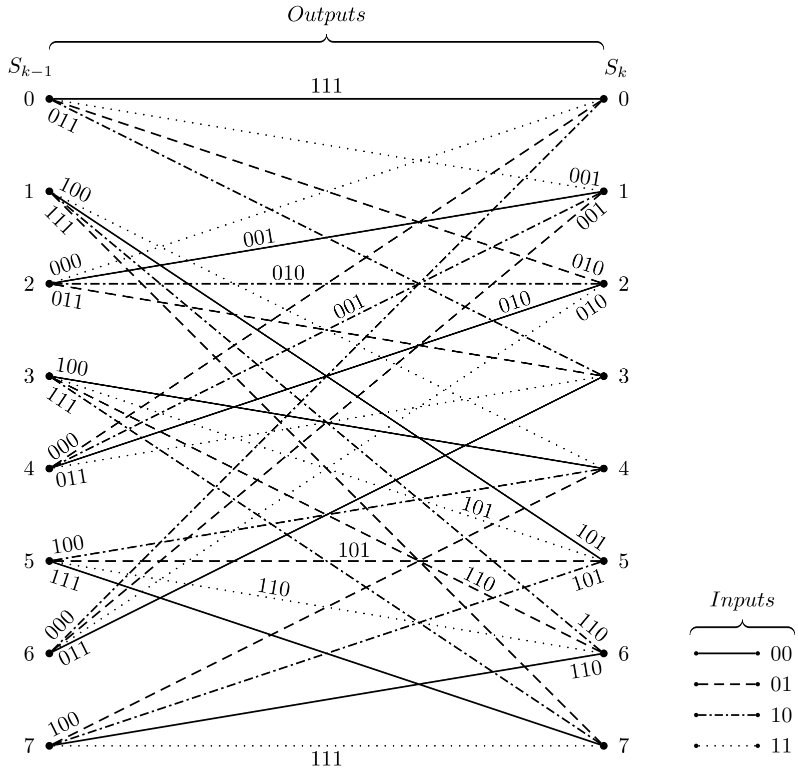



Figure 4.11: Trellis Representation of IEEE 1901 RSC Encoder

The interleaving scheme was implemented using the following algorithm described in the standard:

**Algorithm 1:** Encoder Interleaving Process

**Input**: input binary sequence
**Output**: encoded binary sequence
**for** $x \leftarrow 1$ ***to*** $L - 1$ **do**
  **if** $x$ *mod 2* **then**
    output(2x) = input(2·I(x));
    output(2x+1) = input(2·I(x)+1);
  **else**
    output(2x) = input(2·I(x)+1);
    output(2x+1) = input(2·I(x));
  **end**
**end**

Another particularity of this encoder resides in the termination mechanism, also known as tail-bitten or tailbiting.

Typically in these encoders the binary sequence to be sent undergoes a closing process through which the encoder reaches a pre-defined state commonly designate as closing state that in some cases is known before the decoding process is started. This procedure is often considered as a form of including additional information that can be used in the decoding process. The objective is the recovery of the binary sequence originally sent, after being subjected to error-prone media. This state in non-recursive encoders is fairly easy to calculate through a direct matrix operation and typically corresponds to the zero state, meaning that the encoder memory contains only zeroes. It is known that tail-bitten schemes in feedback encoders can be cumbersome, and in some cases can lead to additional failures that take place in the decoding procedure. In [129] the tailbiting mechanisms for feedback encoders and its pitfalls are thoroughly analyzed and explained.

Depending on the type and architecture of the encoder, namely the memory and consequently the constraint length, and the sequence to be encoded, it may be necessary to input a non-negligible sequence of bits to ensure the convergence to the predefined closing state. In RSC encoders it is possible to have a sequence in which the initial state of the encoder is exactly the same of the final state after the bit sequence has traversed the encoder; this is called a circular state. This is only possible because of the limited number of PBs, for which a series of recursive operations will yield a periodic state sequence repetition. Like in the case where the final state is known, the use of a circular state also allows more information to be available in the decoding processing where an estimate for this state must be nevertheless performed. However this estimation benefits from the fact that the initial and final states are the same: the circular state. Moreover, this method allows the encoding process to be more efficient since it does not require the injection of an extra bit sequence to reach a closing state.

This circular tail-bitten mechanism is stipulated in the standard and it is implemented with two passages of the information bit sequence through the two RSC encoders in order to determine the encoder circular state. It is determined by $S^1_{init} = S^0_{final} \cdot M$, where $S^0_{final}$ corresponds to the final state of the encoder after the first passage and $S^1_{init}$ corresponds to the desired circular state, which by definition must equal the $S^1_{final}$ that corresponds to the final state of the encoder at the end of the second passage. As it was mentioned earlier, by definition, the initial $S_{init}$ state before initiating the tail-bitten scheme is always considered to be zero.

The simplified transmission scheme presented previously includes a channel interleaver that is used to change the bit order of the encoded binary sequence, $x_k$ to $x^P_k$. The interleaving process has little impact on the overall system performance since the channel is considered to be memoryless. However since the Additive White Gaussian Noise (AWGN) implementation is based on a random number generator, as unlikely as it may be, the presence of burst errors is still possible. Furthermore, this implementation is ready to include other implementations of the channel model, where specific types of error patterns can be considered allowing the test of the FEC mechanism. In such cases it becomes important to ensure the "de-interleaving" of the error bursts, as presented below.

The interleaver implementation is made through tables of nibbles that are constructed separately for information and parity bits. The table contains 4 columns with each one containing $k/4$ bits in the case of binary information sequences and $(n-k)/4$ for the case of parity sequences.

The nibbles are sorted according to predefined sequences that depend on the physical block size and the specified code rate, $c$. Two additional parameters, based on the first two, are used to calculate the sequence ordering indices: the offset, $o$, and the step size, $s$. These parameters are available in Table 13-16 of [67] and the sorting index of each row of the nibble table is defined by Eq. 4.6a for information nibbles whereas Eq. 4.6b is applied to the indexing of parity bits.

$$S_{\text{info}}[i] = \begin{cases} \frac{k}{4} - s + i, & \text{if } i \in [\frac{k}{4s}, \frac{2k}{4s}, \ldots, k] \\ \frac{k}{4}i, & \text{otherwise} \end{cases} \quad , \quad \forall i \in [0, \ldots, k] \tag{4.6a}$$

$$S_{\text{parity}}[i] = \begin{cases} (o + i \cdot s + \frac{4 \cdot s \cdot i}{k}) \text{ div } \left(\frac{n-k}{4}\right), & \text{if } c = 1/2 \\ (o + i \cdot s) \text{ div } \left(\frac{n-k}{4}\right), & \text{otherwise} \end{cases} \tag{4.6b}$$

Afterwards, the nibbles from the information and parity tables are extracted proportionally to the code rate in a row-wise operation and are combined to produce a single table of nibbles.

An additional sub-bank interleaving mechanism is used to interleave even further the encoded sequence. It is based on a column-wise sorting strategy according to five different patterns that are used separately in a circular fashion in every pair of nibbles, whether they contain information, parity or both. The implemented sub-bank mechanism is based on the switching order defined on Table 13-17 of [67].

The mapper block is responsible for associating the encoded and interleaved bit sequence to the different modulation schemes, the assignment of phase angles to carriers, empty tone filling and last symbol padding. For simplicity, the mapper presented here assumes that the sequence to be transmitted has the necessary size to match the selected modulation scheme and only one subcarrier is considered. The mapping procedure is performed using the definitions of tables 13-22 through to 13-25, presented in [67], which ensure a Gray coding scheme, meaning that regular modulations from BPSK up to 4096-QAM, including the non-regular 8-QAM, can be used to map encoded sequences. The mapper implements also power normalization, which for square modulations, M-QAM, can be implemented with [130]: $P_{Norm} = \frac{1}{\sqrt{2/3(M-1)}}$; whereas for the non-square 8-QAM is implemented through: $P_{Norm} = \frac{1}{\sqrt{5+1.29^2}}$.

**Algorithm 2:** Combined Information and Parity Nibble Interleaving

```
Input: input nibbles from information table and parity table
Output: interleaved nibbles from
while There are nibbles available from the information table do
    switch codeRate do
        case '1/2'
            Get 1 nibble from information table;
            Get 1 nibble from parity table;
        end
        case '16/21'
            for i = 1 to 5 do
                Get 3 nibbles from information table;
                Get 1 nibble from parity table;
            end
            Get 1 nibble from information table;
        end
        case '16/18'
            Get 3 nibbles from information table;
            Get 1 nibble from parity table;
            Get 5 nibbles from information table;
        end
    endsw
end
```

An AWGN channel was considered as the transmission medium, which was implemented through a random number generator based on a normal distribution, presented in Eq. 4.3. Since there is a power normalization of the transmitted signal the AWGN channel is typically defined by a $\mu = 0$ and a $\sigma = \frac{1}{\sqrt{2 \cdot C \cdot E_s/N_0}}$.

The decoding process in general is not defined in the IEEE 1901 standard and as such its implementation, like the one presented in this section, represents a possible solution among many. Although the implementation of some of the decoding components is already well established, there are some that depend on the specific implementation strategy of the decoder, as it will be shown.

The de-mapper presented in Fig. 4.7 is typically a soft de-mapper, which converts the received signal into estimates of constellation points that were used in the mapping procedure according to a specific modulation scheme. For simplicity, it is assumed that the modulation scheme is known at the receiving end, allowing the correct estimation procedure to be used in the de-mapper.

The soft de-mapping process if often designated as a soft-bit calculation mechanism and it consists in an estimation technique that is performed orthogonally, the exception being the case of BPSK that only has an in-phase component. The estimation process makes use of boundaries associated with each of the different constellation points of the modulation schemes defined in the standard. Each boundary represents the variation of one bit in the received sequence. This occurs because of the previously mentioned Gray encoding scheme. This allows for different estimates to be calculated for each bit of each constellation point of the received signal, according to the boundaries, which define decision regions, of each of the received bits. An example of the referred boundaries can be found in Fig. 4.12 for 16-QAM constellation, where the decision regions of the first two bits are illustrated. The left hand side shows the regions where the first bit of the received constellation point can be either a zero, light region, or a one, dark region. On the right hand side the same regions are presented for the second bit. Despite the fact that only the decision regions of the in-phase bits of the 16-QAM constellation symbols are represented, the same rationale applies to the orthogonal binary component where the same decision regions can be devised even in parallel.

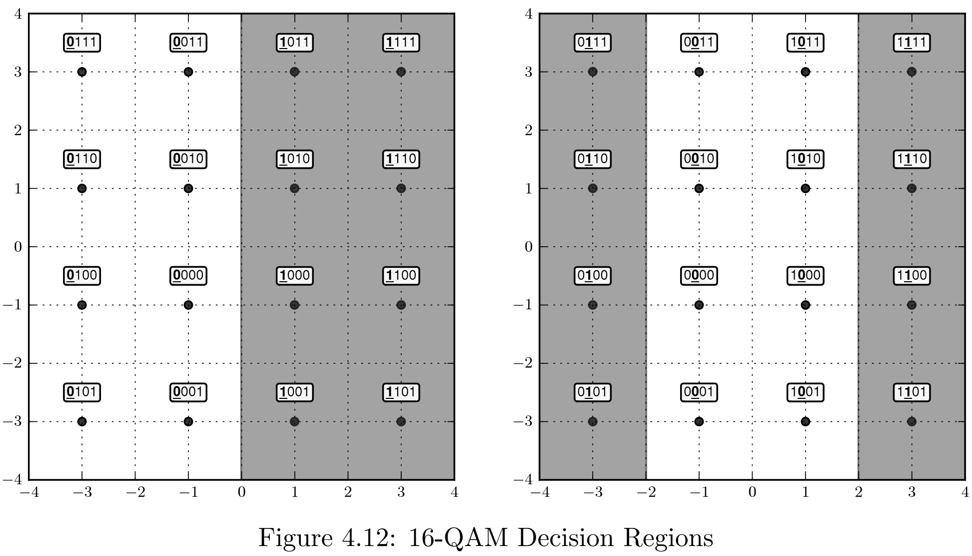



Figure 4.12: 16-QAM Decision Regions

When considering hard de-mapping the received bit constellation symbol is immediately converted to a bit sequence according to different decision regions. There is no sense of certainty regarding the likelihood of a determined received constellation symbol be either a zero or a one. This is precisely the advantage of the soft-bit produced by the soft de-mapping process. Hence, a metric is used, which expresses the degree of certainty that a particular bit, $r$ of a received sequence is either a "1" or a "0". This metric is called Log-Likelihood Ratio (LLR) and is defined in Eq. 4.7 [131]. This definition will be revisited at a later stage.

$$\Lambda(r) = \log \frac{p(r|b=1)}{p(r|b=0)} \tag{4.7}$$

More information about the formulation used for soft-decoding estimation used in the implementation of soft de-mapper considering square constellations from 16-QAM up to 256-QAM can be found in Appendix E. A hard de-mapper version was also implemented, to allow the comparison between hard and soft decoding and the respective advantages when using the latter together with complementary estimation techniques used in the decoder block.

The channel de-interleaver of Fig. 4.7 transforms the received noisy sequence back to its original order, by permuting each bit according to the inverse version of the interleaving pattern used to encode the sequence. The implementation is thus a mirrored version of the channel interleaver, with the input sequence being converted to a nibble table over which the sub-bank de-interleaving process is carried out in a column-wise fashion. A row-wise nibble re-ordering scheme follows, which separates the previous table in two, containing information and parity respectively. Finally a re-ordering process is executed within the nibbles and separates the information and parity sequences at the receiver.

The decoder module is responsible for converting the receive sequence, $y_k$, into a sequence of estimates, $\hat{u}_k$ of the original sequence, $u_k$. The decoding process follows the de-mapper estimation, which produced a sequence of soft-bits in the form of LLR, containing information, often called *a priori* information, to help the decoder to effectively provide an accurate estimate despite the uncertainty introduced by noise in the communications channel.

The type of decoders used within these encoding/decoding systems is designated as turbo decoders due to the iterative decoding process, which resembles the operation of a ICE turbo feedback mechanism. These decoders presented by Berrou, Glavieux and Thitimajshima [132] were major breakthrough in error correction coding, allowing near-Shannon limit operation. The adoption of turbo codes and their study has been intensely carried out by the research community and one of the most famous implementations was used in deep space communications [133, 134]. The typical architecture of these decoders is presented in Fig. 4.13.

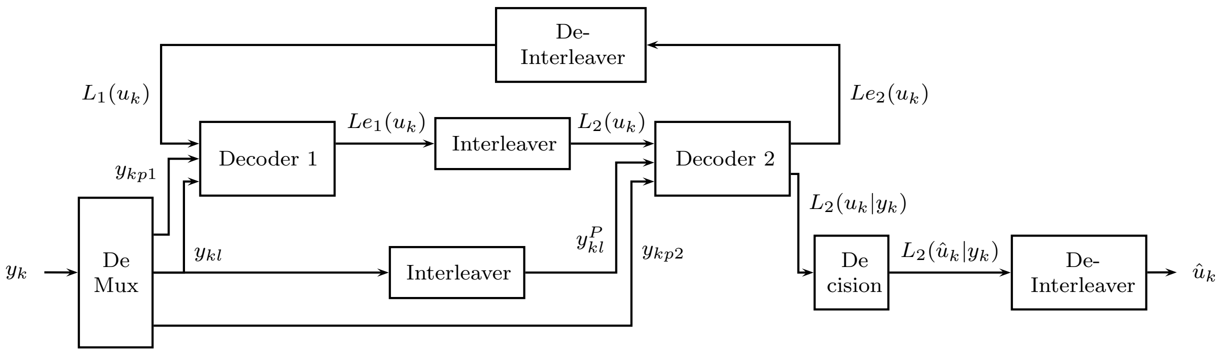



Figure 4.13: Turbo Decoder Architecture

It is composed of two internal decoders that receive as input the information and parity binary sequences estimates, along with an *a priori* probability value, to produce a Maximum *a posteriori* Probability (M$a$P) value, which will feed at a later stage a decision block that will output the estimated binary sequence in a hard decision process. The iterative nature of this decoder is associated with the feedback loop of the M$a$P value deemed from the second decoder, which is used as the *a priori* information fed into the first encoder. This iterative process can be triggered a limited number of times in order to stabilize the estimation process, after which there are no significant changes that could influence the decision block regarding the output binary estimate sequence. In this regard a stopping criteria base on cross-entropy is shown in [135] to provide a good value for the minimum number of iterations. Interleavers and de-interleavers are used to synchronize the binary information and parity sequences at different stages of the iterative process. A de-multiplexer is used to extract the information, $y_{kl}$, and parity sequences $y_{kp1}$ and $y_{kp2}$, from the received, $y_k$, sequence.

In each of these decoders a forward-backward decoding algorithm was implemented based on the well-known BCJR optimal decoding algorithm [136] along with M$a$P variants. A particularity of the IEEE 1901 encoding system, already mentioned, is the non-binary nature of the encoding process which implies some changes to be implemented when compared to the classic binary decoding. The main change is related with the processing of the decoding sequence that is performed in pairs of bits or dibits.

The decoding process is described in detail in Appendix F, with the respective mathematical formulation used in implementing this block and the basics of turbo decoding that underlie this type of implementation. The BCJR decoding algorithm was implemented along with the M$a$P and log-M$a$P variants, mainly due to their dissemination in this area, and in the latter due to the increased performance in the overall decoding process time.

A preliminary phase, also known as prologue, needs to be carried out in the decoding process in order to estimate the circular state of the encoded sequence. As already mentioned the sequence to be encoded undergoes a tail-bitten process, to allow a circular state to be associated with the sequence to be sent. In [137] this circular state estimation is approached and conveniently illustrated under the form of a circular trellis, which results from the concatenation of several trellises like the one presented in Fig. 4.11. Since the circular state depends on the encoded sequence, it is unknown to the decoder.

As highlighted in [137] the estimation of the circular state can be implemented by means of two types of algorithms. The so called optimum algorithms assume a uniform distribution of states along with the fact that the initial and final states are the same. The called sub-optimal algorithms make use of the M$a$P decoding scheme by traversing the circular trellis a limited number of times until the first and last states are identical. These algorithms represent an overhead to the decoding process, which will make use of the circular state, as a useful extra information, to improve the overall estimate of the decoded sequence. The sub-optimal algorithms require even a change to the legacy BCJR decoding algorithm or M$a$P variants in order to combine the circular state estimation with the turbo decoding mechanism.

In order to eliminate the overhead of this pre-computing process an alternative approach was implemented which uses the feedback nature of the decoding structure to avoid the estimation of the circular state [138]. This method, where the borderline decoding metrics $\alpha$ and $\beta$ from previous iterations are used to enhance the respective estimates, was shown to achieve very good results while keeping the decoding process simple [139, 140]. This approach is described by Eq. 4.8 where $t$ represents the iteration number and $N$ the number of pairs of bits (or dibits) present in the binary sequence to be decoded. This yields a small change to the decoder architecture presented earlier, as illustrated in Fig. 4.14, with the feedback of $\alpha$ and $\beta$.

$$\alpha_0^t = \begin{cases} 0 & \text{for t} = 1 \\ \alpha_N^{t-1} & \text{for t} > 1, \end{cases}$$
$$\text{where, t} \in \mathbb{N} \tag{4.8}$$
$$\beta_N^t = \begin{cases} 0 & \text{for t} = 1 \\ \beta_0^{t-1} & \text{for t} > 1, \end{cases}$$

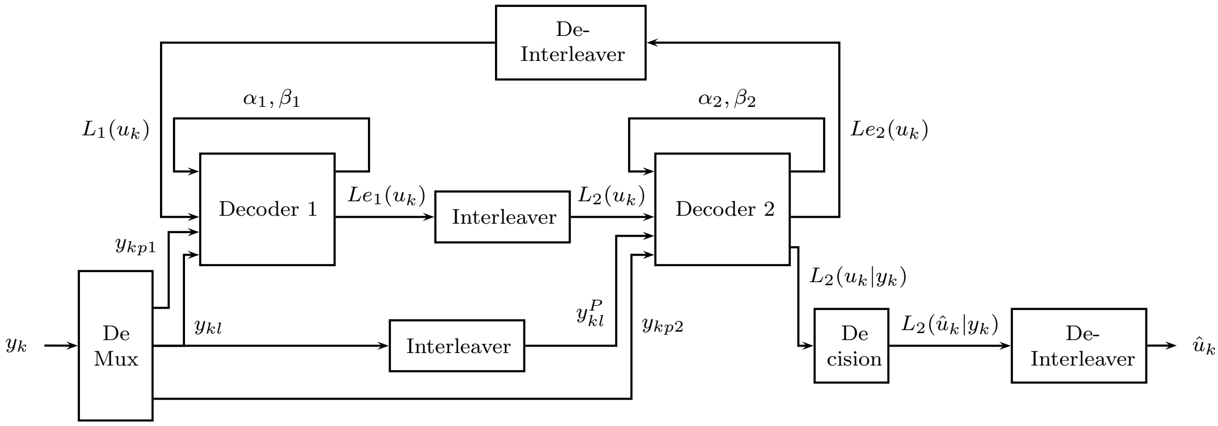



Figure 4.14: Turbo Decoder Architecture with Borderline Metric Feedback

### 4.5.2 Performance of the Simulation System

The heavy recursive nature of turbo decoding systems translates into an intensive computational effort to process a complete binary or non-binary encoding and consequent decoding process. This is a know issue when simulating these type of systems where the computation is performed in a symbol-wise fashion and the number of calculations is dependent on the bits per symbol and the depth of the specific encoding scheme [141]. The burden is placed mainly on the decoding process and the complexity can be better understood when analyzing the encoder trellis depicted in Fig. 4.11. For each received symbol 32 possible transitions need to be evaluated, with the branch calculations, along with 8 state forward and backwards metrics, as highlighted in Appendix F.

This system was implemented in an optimized fashion using Python, which allowed for a faster implementation of the presented solution but at the cost of limited performance degradation when compared to other languages, namely `C/C++`. A considerable investment was made in optimizing the performance of the implemented system by incorporating good practices in writing each module and the use of speed oriented routines that were evaluated by profiling the code execution and identifying potential bottlenecks at run-time. The use of performance oriented extensions like Cython and alike, with partial coding being implemented in `C/C++`, shows some improvement and its usage was also considered.

However, given that the heaviest numerical calculations, involving the manipulation of matrix-oriented metrics, were performed through the NumPy module, a specific version using the Intel MKL library[4] was used. Unlike Cython where specific static declarations implied code re-writing and adaptation, the MKL version yielded no changes to be implemented. Moreover, the multi-core nature of current CPUs led to the use of multiprocessing characteristics to deal with the inherent hidden Markov formulation present in the turbo decoding block. The use of parallelization was also explored in the implementation of a Monte Carlo simulation scheme to evaluate the changes introduced by the associated random number generators.

## 4.6 Specification of the Laboratory Communications Infrastructure

One of the main goals of the REIVE project was the conception, design and deployment of an electric mobility laboratory. The specification of this laboratory considering both the electric and communications networks, is described in this section as part of the work performed within this thesis. It is a modular solution to accommodate current and future smart grid trends.

The main objective of this infrastructure is to have a near-real simulation tool to test and evaluate monitoring and control strategies envisaged and developed according to the SG paradigm considering the technical operation perspective, as referred to in previous chapters. It also includes a reconfigurable and testable communications infrastructure to analyze and assess different communications technologies and solutions.

The laboratory was designed to integrate diverse equipment (commercial and prototypes), control systems and software modules that are used to test and evaluate, individually or in an integrated fashion, concepts such as control algorithms, decision making strategies, communications solutions and information exchange schemes allowing the necessary conditions towards the operation of microgrids under normal (interconnected) or emergency (isolated) modes. The laboratory follows the hierarchical control architecture from the microgrids concept, allowing the implementation of both centralized and distributed control functionalities.

### 4.6.1 Electric Network

The laboratory was conceived to integrate an electrical infrastructure composed of several different devices. Among them are commercial inverters (with different control schemes: P-Q inverters and Voltage Source Inverters (VSI)), solar panels, a wind turbine emulator, batteries (lead-acid and lithium-ion), a slow charging station, an electric vehicle and a set of emulating systems, among which are cable emulators. Several custom tailored prototypes, which include a solar and a wind inverter along with an EV charger, were developed with specific control characteristics, based on voltage and frequency droop that can be configured to determined scenarios, which are not commonly available in current commercial solutions.

The electric network also includes all the protection and automation devices controlled by a centralized SCADA system, which incorporates the necessary monitoring and metering devices, enabling a system

[4] Available at: http://software.intel.com/en-us/intel-mkl

with enhanced management and control features. The SCADA architecture is depicted in Fig. 4.15. The electric infrastructure allows a flexible composition of two different LV microgrids with configurable and controllable energy portfolio. It is thus possible to have two MGs that are able to operate interconnected with the low voltage distribution grid or isolated, using VSIs that have grid forming capabilities. Beside the commercial systems, it also allows the inclusion of prototypes with enhanced control and operation characteristics towards the integration of microgeneration and electric vehicles. A four-quadrant back-to-back inverter is also available that can be remotely controlled in terms of injected or absorbed electric current allowing the emulation of a controllable microsource, like a microturbine or a fuel-cell, or of a controllable load.


Figure 4.15: Laboratory SCADA Architecture

The laboratory management and control architecture, depicted in Fig. 4.16, is divided into:

- Monitoring and automation system:

    1. Supervisory Control and Data Acquisition (SCADA): the system responsible for the centralized monitoring and control of the laboratory electric network;

    2. Remote Terminal Units (RTU): to allow data collection (metering, state, etc.) and the interaction with local actuators (switches, contactors, etc.) integrated in the SCADA system.

- Smart management and control system: a hierarchical control structure based on microgrids and multi-microgrids concepts was implemented, exploring the different communications gateways provided by the laboratory infrastructure. These entities consist of processing units and respective software modules, which are responsible for the management and control of the different hierarchical levels:

1. Distribution Management and Control System (DM&CS): the system is responsible for the integrated management of the two microgrids and the direct interaction with the SCADA system through which the lower level is reached. It inherits some of the functionalities found in typical DMS and in the managing entity of multi-microgrids, the CAMC;
2. Microgrid Central Controller (MGCC): is the entity responsible for local management and control of each microgrid and interacts with the upper DM&CS and the lower EBs through the RTU;
3. Energy Box (EB): is the local smart metering system with local control and management capabilities to be found in the customer premises, with the ability to emulate different control schemes associated with loads, microgeneration or EVs;
4. Local Controllers: local software tailored for control and management of specific devices such as loads (LC - Load Controller), microgenerators (MC - Microgeneration Controller) and electric vehicles (VC - Vehicle Controller).

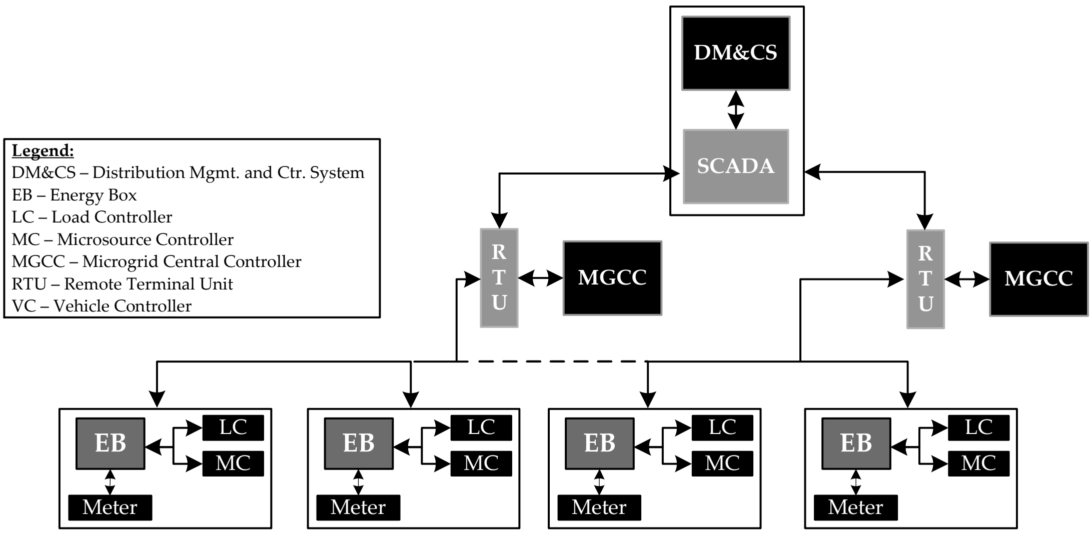



Figure 4.16: Laboratory Management and Control Structure

The dashed line in Fig. 4.16 represents the ability to reconfigure the portfolio of each microgrid, which may include in an extreme case the connection of all EB elements under a single MGCC. In order to provide a flexible development platform, PCs were used to implement the functionalities of MGGC and EB nodes. As such these nodes can be equipped with different communication interfaces, while allowing computing capability to run control algorithms and to test different graphical interfaces. The local controllers (LC, MC and VC) are also associated with PCs that mainly operate as gateways that allow the remote configuration of parameters in the dedicated control hardware.

### 4.6.2 Communications Network

A communications solution was designed to interconnect the backbone SCADA system, typically found in a substation environment and also used in this scope for supervision and automation purposes, with other devices that compose the smart grid laboratory. Fig. 4.17 is a representation of the communications architecture that supports the laboratory, with the links between the control structure, the SCADA system and the end applications through EBs, either for general LV and MV customers or specifically for electric vehicle charging applications. All the communications links have associated a Medium Behavior Controller (MBC) which is an optional software entity responsible for the emulation of the communication medium according to propagation characteristics, bandwidth, delays and losses, which are variables typically associated with the performance of communications systems.

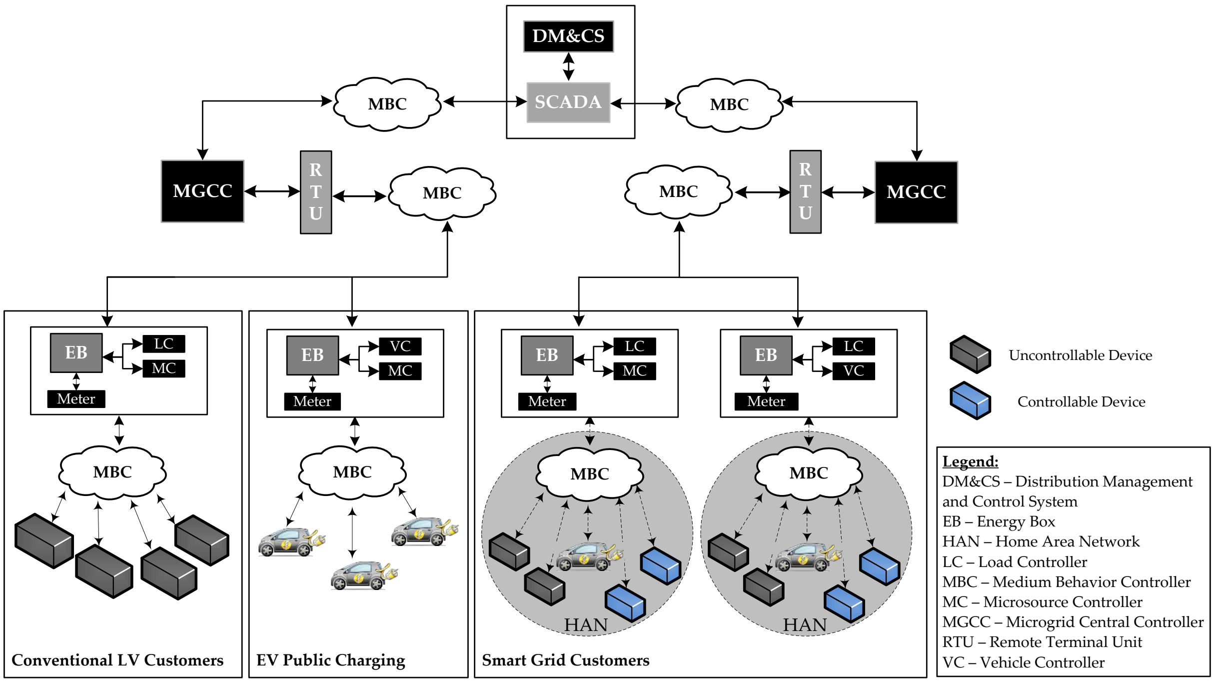



Figure 4.17: Laboratory Communications Architecture

The SCADA system has an independent and physically separated communications infrastructure that integrates devices from different manufacturers as well as the hardware prototypes (solar, wind, EV) specifically developed for the laboratory. The SCADA architecture presented in Fig. 4.15 consists of a front-end node connected to RTUs via Ethernet, which in turn are capable of exchanging data, for example, with the inverters and metering devices, through serial buses (RS-232 and RS-485) and all the associated standardized SCADA communications protocols. The physical separation of the laboratory communications network from the SCADA network was an intentional decision since the latter is responsible for the management, control and automation of the electric devices in the laboratory where protection schemes and supervision functionalities are implemented. This allows the exploration of different communications scenarios independently, considering the necessary communications configurations to emulate different links and technologies, without compromising the performance of the SCADA system.

Fig. 4.18 illustrates the integration of the SCADA system with the communications infrastructure considered for the laboratory and the control nodes envisaged in the previously mentioned microgrid strategies. The laboratory communications network can be thought as an overlaid solution over the SCADA system.

A full duplex Ethernet based solution was deployed as the basic communications infrastructure designed to emulate the communications found in the distribution and end customer segments of smart grids. This cabled solution represents virtually an unlimited bandwidth and noiseless data exchange medium over which some control will be effectively performed by means of MBCs. Hence, the usage of MBCs allows the emulation of different technologies and scenarios of application by introducing controlled packet loss schemes, delay variation, jitter, simulation of loss of connectivity and other phenomena associated with real communications channels and networks. The implementation of the MBC is performed through software modules, which are responsible for the management and control of the information flows associated with communications interfaces of the different nodes (PCs) participating in the laboratory network. These modules are responsible for the interaction with the communications interface drivers and operating system kernel configurations to set different communication scenarios.

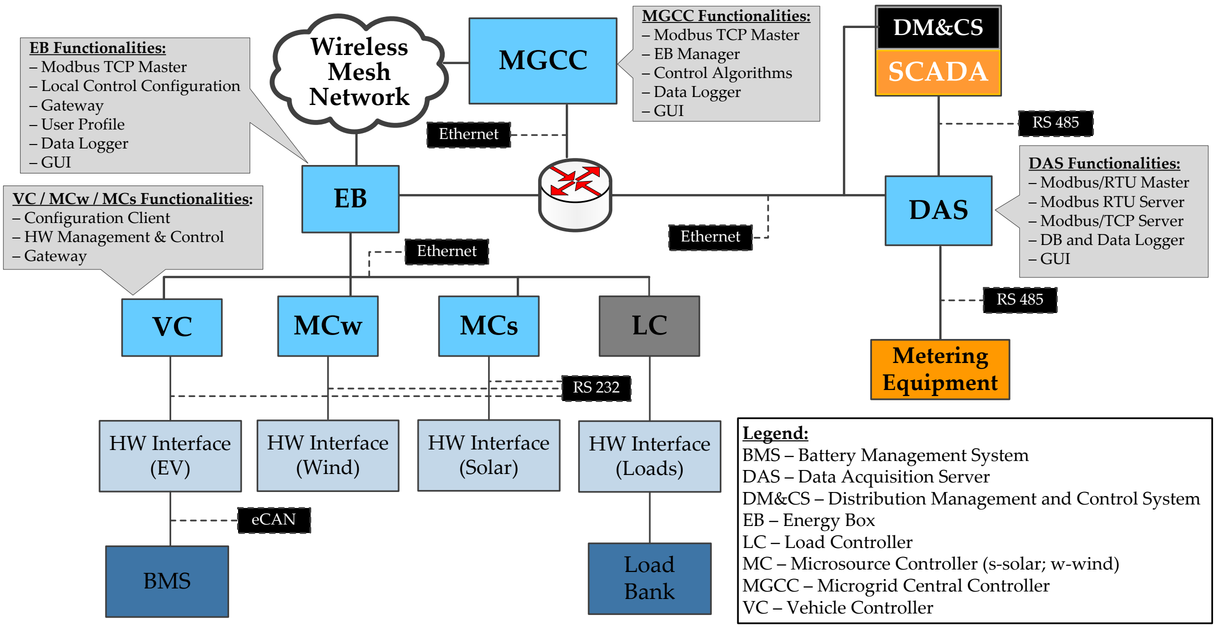



Figure 4.18: Laboratory SCADA and Communications Network Integration

The communication links and the respective technology are represented in Fig. 4.18 between all the different participating entities of the laboratory. For simplicity only unique entities are represented, but it is possible to establish configurations with multiple nodes. As already referred the MGCC and EBs are implemented in PCs as well as the local controllers, with the exception being the load controller which is implemented though a software module in the EB that is able to remotely activate different banks of load. The PCs are equipped with the necessary gateway and protocol conversion mechanisms to ensure the interaction with different interfaces other than the Ethernet communications network.

The Data Acquisition Server (DAS) is a module also running in a PC designed to collect metering information from all the Modbus meters installed in the laboratory via RS-485 Modbus/RTU. It can be configured to work as a Modbus/TCP server allowing the different control entities, including the SCADA, to collect metering information. The metering data can requests are configurable with variable registers (measurements) and periodicity.

The SCADA system uses a common RS-485 bus to collect metering data via the DAS, and an independent Ethernet interface from SCADA through which the DM&CS is able to interact with the remainder control elements. The DM&CS is implemented as a SW module that interacts directly with the SCADA front-end, allowing control orders to be immediately dispatched.

A Wireless Mesh Network (WMN) was implemented as an alternative to the Ethernet cabled solution. This WMN extends over the faculty campus and it implements a multi-hop communications infrastructure that is able to convey control data over a communications network deployed in a real-world environment. The laboratory communicating nodes are thus able to select over which network the data should be exchanged. This is accomplished by means of selecting the respective communication interface.

### 4.6.3 Communications Uncertainty

In order to evaluate the operation of a microgrid hierarchical control structure a set of operating scenarios must be defined. These scenarios tend to favor the introduction of particular operation aspects to be evaluated, while allowing the assessment of the impact of communications, by introducing uncertainty in terms of losses and delays over the controllable communications infrastructure. These uncertainties are emulated at the kernel level of the operating system running in each of the nodes that participate in the microgrid hierarchical control scheme. Furthermore, is it possible to define the values for jitter and bandwidth to be associated with each of the communications interface of each node.

To evaluate the impact of communications it is necessary to ensure that the operating conditions are kept stable as much as possible to allow a faithful comparison between different scenarios. As such, a synchronized sequence of events can be defined to evaluate the control and operation of a microgrid, considering both the local control as well as the centralized control. The controllable nodes can be configured to react to different operating conditions, allowing a diverse set of scenarios to be explored. A set of software modules were developed to allow the remote configuration of the different local controllers by issuing set-points containing several parameters. It also allows the remote configuration of the communications parameters of target controllers for the emulation of different channel conditions.

Different control functionalities were established, namely voltage and frequency control, which are triggered according to the MG operation mode. For the voltage control the laboratory microgrid is operating interconnected with the MV network where a set of events are assumed to occur and the control structure reacts accordingly. As far as the frequency control is concerned the microgrid is set to operate in isolated mode that occurs after a blackout has been originated due to a disturbance in the MV, requiring a black start procedure to ensure the system recovery. A black start is a response to a blackout event produced by an upstream disturbance and where an immediate reconnection to the upstream network is not possible. It is emulated through the disconnection of the laboratory microgrid from the distribution network. The black start consists of a series of events in a procedure triggered by the LV network controller, the MGCC, involving a predefined sequence of events [38]:

1. The MG status is evaluated by the MGCC and the black start is initiated if the system operation is not able to reconnect the MG to the upstream network due to the severity of the disturbance. The MGCC collects information of the MG current state to detect anomalies and determine the available controllable resources, typically generation and active loads;

2. The MGCC prepares the MG for the restoration process by issuing signals to local controllers to ensure that microsources (MS) and loads are disconnected. The MS with black start local control capabilities are started to provide storage and capability to feed local loads;

3. The MG is energized through the closing of the respective LV feeder switches allowing the storage units with grid forming capability to ensure the necessary voltage and frequency conditions for the network to operate;

4. The power-frequency droop control of the EV charger is activated with a zero active power set-point, allowing it to participate in the isolated system frequency control;

5. The remaining loads and non-controllable MS are connected considering the available reserve capacity, preventing large frequency and voltage deviations allowing the system to operate within predefined bounds;

6. After all generation is activated the EV support is no longer necessary and it can take advantage of existing MS to start charging its batteries.

The specific events and associated control sequences, further detailed in Chapter 5, require a set of control and management actions, both local and centralized, to ensure that the system has the adequate power quality levels and stability when operating in isolated mode. Hence, different local voltage and frequency control mechanisms can be explored using configurable droop control characteristics that are dependent on the local controller functionalities, allowing the centralized control capabilities to deal with the overall system response.

A communications infrastructure was implemented to support the interconnection of the different entities within the microgrid control scheme, as depicted previously in Fig. 4.18. A full IP-based Ethernet ensures the necessary connectivity between control entities and electric devices that are able to be remotely controlled. The MGCC represents the central node of the laboratory microgrid and is responsible for the remote setup of the operation conditions to be tested and it is able to exchange information with different EB nodes under its supervision. The MGCC is also capable of interacting with the SCADA system and issuing remote orders to the DM&CS entity, allowing the configuration of an electric network topology for a specific test.

Each EB node operates as a communications gateway and is able to configure different types of local controllers and to issue control set-points that are originated by the EB itself or to forward a control configuration request from the MGCC. The EB nodes are also equipped with a SW module that is responsible for the emulation of the communications channel characteristics. This module was developed and implemented in the scope of this thesis to allow its configuration both locally or remotely for each test. This module has associated a TCP/UDP server that can be configured to act as a simple gateway to local controllers over which communications uncertainties may be activate or not. Hence the suppression of the communications emulation can be used for configuring and defining an operation scenario where an automated sequence of events is triggered that mainly concern the connection or disconnection of laboratory equipment. Conversely the activation of the communications emulation allows the evaluation of different control strategies by introducing uncertainty in the control set-point exchange mechanism.

## 4.7 Summary and Main Conclusions

The implementation of communications networks to support different smart grid applications will have to consider the associated requirements and the definition of communications solutions capable to meet them. This chapter presented the control strategies used in the system operation of distribution networks. For this purpose it is assumed that private networks, typically owned and operated by system operators, are used support hierarchical control structures like those associated with multi-microgrids (MMG). In Section 4.2 the methodological aspects of the implementation of a MMG control system were presented along with the introduction of uncertainties related with the communications networks that support the control scheme and associated set-point exchange mechanism. An integrated tool that was developed for this purpose was presented; it allows the evaluation of the impact of such uncertainties in the operation of MV distribution system considering a diversity of scenarios created through a Monte Carlo implementation.

The importance of the context characterization was approached in Section 4.3 where a specific tool, based on graphs, was developed to process data from real feeders. Moreover a goodness of fit procedure was defined to allow the geographic characterization of distributions feeders, using data provided by the Portuguese DSO. This methodology sets the basis for the development of another tool that allows creating scenarios with different node positioning strategies based on different PDFs associated with the random number generation procedure. It provides synthetic data containing the number of potentially communicating nodes and their respective positions according to pre-defined types of distribution networks.

Section 4.4 presented a WMN implementation for electric distribution networks, in which the tool for random generation of scenarios was used and the methodology for the installation of WiFIX networks as well as associated algorithms when considering different types of distribution networks were defined. A polling scheme was proposed as a flexible scheduling algorithm that is compatible with the centralized control approach used in MMG. It is able accommodate the variability in terms of target control set-points to be issued in each control round, without having to transverse all nodes.

In Section 4.5 the IEEE 1901 standard was analyzed and a model for the PHY implementation was proposed, with the corresponding turbo decoder module, to allow the evaluation of the information resilience of the transmission scheme, namely the error correction capabilities of the standard.

Finally in Section 4.6 a laboratory specification was presented with the definition of a communications infrastructure that ensures the remote configuration and operation of the available equipment and the interaction with the SCADA system. This allows different configuration scenarios to be created, in both interconnected or isolated modes of operation, and the evaluation of different control strategies. Furthermore, a communications infrastructure was defined to allow the emulation of communications characteristics that can be associated with different technologies or implementations, namely in terms of loss ratio, data delays and throughput.

# Chapter 5

# Results

## 5.1 Introduction

This chapter addresses the qualitative and quantitative analysis of the results associated with the work developed in this thesis, which was contextualized and detailed in the previous chapter. Section 5.2 analyzes the impact of uncertainties introduced by communications systems in the operation in emergency mode of distribution grids, namely MV and LV, when considering microgrids (MG) and multi-microgrids (MMG) control structures. In Section 5.3 a characterization of Portuguese distribution feeders is presented, considering both LV and MV networks, in order to better understand the context upon which communications systems have to be considered when supporting SG applications and to provide relevant information that allows the definition of likely scenarios that can be found in the distribution segment. Section 5.4 presents simulation results of a wireless mesh network implementation based on WiFIX as an alternative and complementary communications solution to be installed in distribution grids. Different scenarios are established and an evaluation of WiFIX as a valid implementation to support last-mile communications is carried out. In Section 5.5 an assessment of the IEEE 1901 powerline standard from the physical layer perspective is conducted, to understand the robustness of the error correction mechanism in harsh communications environments. A laboratory implementation of a real microgrid control system is presented in Section 5.6, where an evaluation of the communications uncertainties is carried out. Their impact in the operation of different devices participating in the control action of a microgrid system is assessed considering the interconnected and isolated operation. This chapter closes with an overall summary with the main findings and conclusions derived from the results.

## 5.2 Impact of Communications Uncertainty in a Multi-Microgrid System

The need for a communications infrastructures to convey the control data that is able to support the hierarchical control structures present in MGs and in MMGs was widely justified in the previous chapters. However, there is a particular aspect when considering communications, which is the potential uncertainty introduced in the exchange of information. This is more severe in adverse medium such as wireless and

PLC, which are the main candidates for the smart grids communications in the last-mile. Hence, an operating scenario was established involving a MV feeder, depicted in Fig. 5.1, and the respective MMG and MGs control structure. This test network is constituted by two distinct zones, one rural and the other urban, with different characteristics. The rural part of the network is composed of long overhead lines with significant voltage drops, whereas the urban part has shorter and underground electric cables. This network composition was mainly considered to allow a degree of diversity in evaluating the performance of the control scheme while accounting for different electric network characteristics. In this system a considerable number of controllable MV generators and loads is available, allowing enhanced control strategies to be considered in emergency mode operation. The distributed generation is composed of: a small diesel unit; two Combined Heat and Power (CHP) units; two pairs of Doubly-Fed Induction Machines (DFIM) representing wind-farms; and a storage device managed and interfaced with the MV network though a VSI. A more detailed description of the test network composition and associated models can be found in Appendix C, along with the operational costs associated with the participation of the different entities in the secondary control, which are related with the MILP formulation presented in the previous chapter.

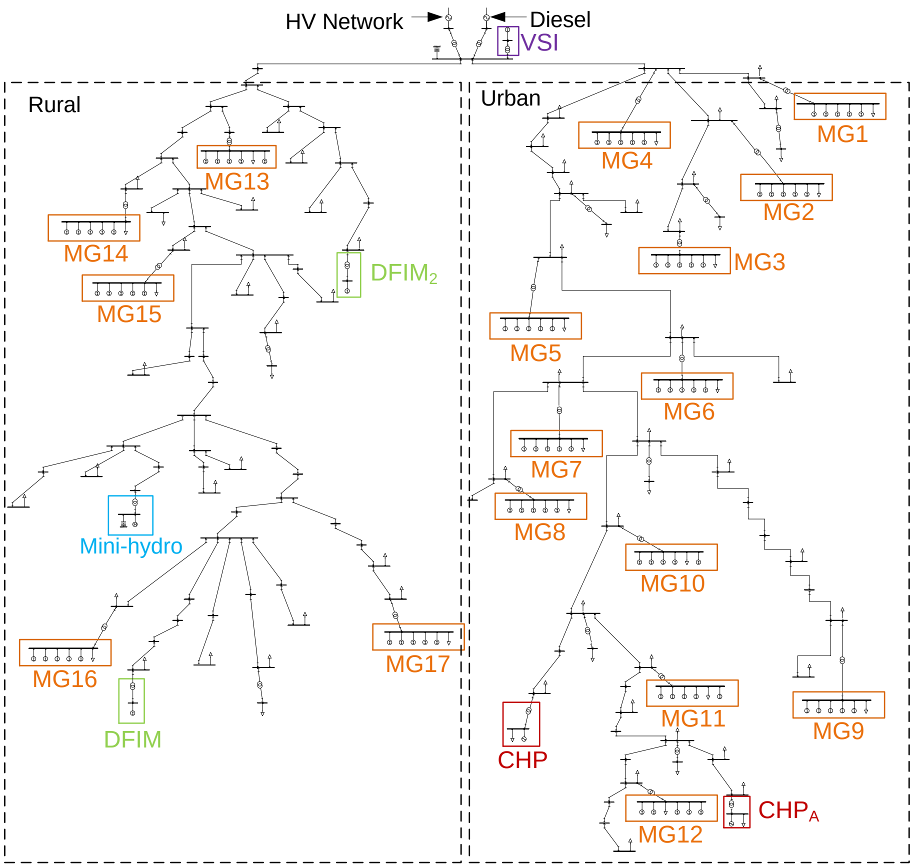



Figure 5.1: Multi-Microgrid

The microgrids are implemented through an aggregated model at MV level, meaning that LV cables are not considered and loads are also aggregated. Each microgrid is typically composed of a variable generation portfolio that may include photovoltaic, micro wind turbines, gas microturbines and fuel cells. Controllable loads as well as storage devices controlled and interfaced by means of VSIs are also available within MGs. Different compositions are thus possible for each microgrid, by activating or deactivating participating entities. Only gas microturbines and controllable loads are set to participate in the secondary frequency control scheme, mainly due to their fast response to power set-point variations. From the available microgrids only six are controllable by the secondary control scheme representing a scenario with limited controllability.

The primary frequency control is also provided by the available VSIs, according to their droop control characteristics. In terms of secondary control a frequency dead-band and a power deviation threshold were established to prevent extemporaneous control actions, as illustrated in Fig. 5.2. It inhibits the centralized control from reacting to small deviations in the system frequency. This allows the primary frequency control and electromechanical transients to stabilize before a new round of set-points is issued. The frequency dead-band is set to 1%, meaning that only outside [49.5, 50.5] Hz band will the secondary control be activated. Similarly, only absolute power deviations beyond 20kW will trigger the necessary issuing of set-points by the secondary control.

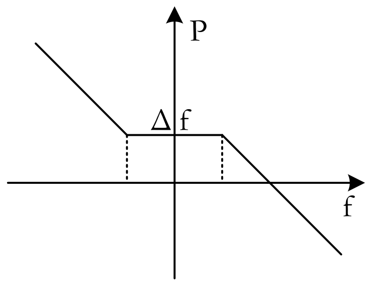
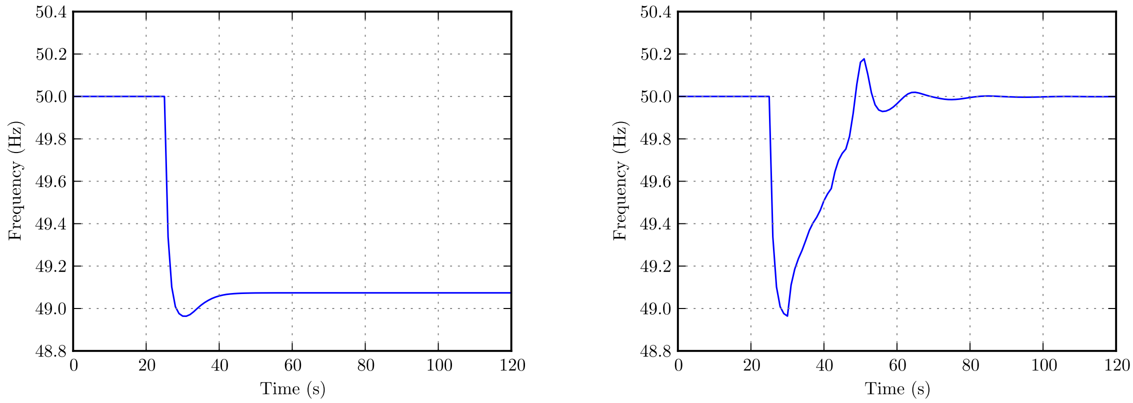



Figure 5.2: MMG Frequency Control Deadband

In this particular scenario an islanding event was introduced in order to evaluate the performance of the control scheme, when ensuring a smooth transition process and the system frequency recovery in a demanding environment. This scenario also allows assessing the impact that communications systems uncertainties can have in the overall system behavior. Prior to the islanding disturbance the MMG is considered to be operating in a steady state and is drawing nearly 4.83 MW of active power from the upstream HV network, which is assumed to be an infinite bus. The available controllable generation inside the MMG totals 4.4 MVA, which means that there is a shortage of power supply to meet the MMG immediate consumption needs after the disturbance. As such, a centralized load shedding strategy was implemented within the control scheme in order to aid in the frequency control. This shedding process is performed in a discrete fashion, where loads are shed in predefined equal steps. The islanding occurs at $t = 25$ s and the MMG control scheme is only aware of the disturbance when a new system observation is performed, which means that it may take up to $t_s$ seconds. This value includes also the time associated with the execution of the control algorithm.

The frequency response of the MMG system to the islanding event is depicted in Fig. 5.3. On the left side, Fig 5.3a illustrates the response when no secondary control action is performed. On the right side,

Fig. 5.3b depicts the same system with the activation of the secondary control under ideal conditions, meaning that set-points are issued without delays or subject to losses. A normal control sample time, $t_s = 5$ s, is assumed when the system is operating in normal condition, whereas a reduced emergency sample time, $t_e = 4$ s, was considered after the disturbance takes place allowing the system to react sooner to the intermediate frequency deviations.




(a) Without Secondary Control (b) With Secondary Control

Figure 5.3: MMG System Frequency Response

A variation in $t_e$ was explored to understand the benefit in terms of system response of having the control system reacting at different sample times, as depicted in Fig. 5.4.

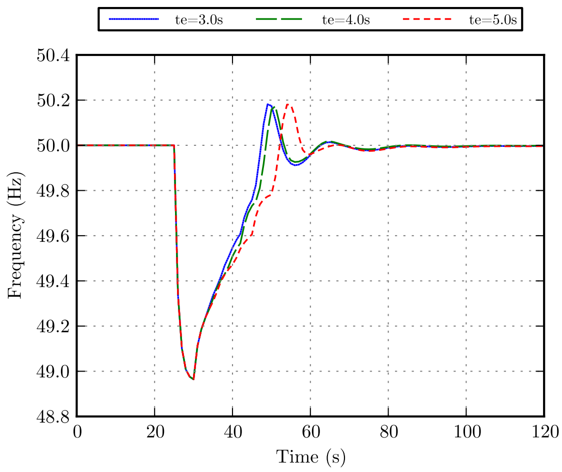



Figure 5.4: MMG Control - Emergency Sample Time Variation

Since $t_s$ value is kept constant in all cases, this means that the initial response is exactly the same, since the control system is aware of the frequency deviation at the same exact moment. The PI-controller parameters had to be adjusted for the different values of $t_e$. As expected, for lower values of $t_e$ and in similar conditions, the control scheme starts reacting earlier since it is aware of the operating state of the

MMG system more often. However, in steady state, only little and generally negligible differences are detectable. This suggests that narrowing down the time between observations, in this case, does not lead to substantial benefits in terms of the overall system frequency response. Since different values of sample time are used, it means that different decisions are taken by the control algorithm. This will become more evident later on when the uncertainty of communications is evaluated. Furthermore, lower $t_e$ values were shown to trigger a larger number of set-points to be exchanged within the frequency control scheme, despite the defined power and frequency threshold values or control dead-bands that can be associated. This may have a negative impact on the mechanical stress induced by the excessive requests of power variation to electric generators, with arguable benefits in terms of the MMG frequency response.

An assessment of the impact of delays was conducted, by introducing a random delay value and jitter to each set-point exchanged at the different levels, MV and LV, of the control scheme. The delay includes the system observation and the time that a set-point takes to be transmitted, processed and implemented. Given that no significant benefits were derived from a lower $t_e$, the intermediate 4s value was used. An example of the impact of delays in the system frequency is illustrated in Fig. 5.5. As defined in the previous chapter this process uses a random number generator, which means that variations can be expected when using the same values for the delays. The MMG secondary control gains were kept constant.

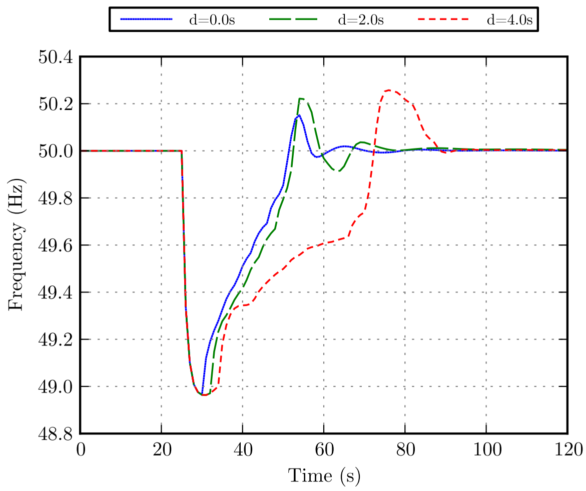



Figure 5.5: MMG System Frequency Response in the Presence of Delays

It is noticeable the effect of a delay, $d$, when associated with the set-point exchange scheme, namely in the system frequency response. In the case where $d = 2.0$ s there is a deviation from the ideal case, $d = 0.0$ s, and a higher oscillation of the frequency value, but the nominal frequency value is fully restored. Nonetheless in the case where $d = 4.0$ s the consequences are clearly visible, with a substantially delayed response and a slower steady state convergence. One important aspect to consider is that the $t_e$ value is very close to the necessary time to send a set-point from the CAMC to any of the MV controllable entities. This means that, due to the presence of variable delays, newer set-points can potentially be sent before the previous ones are received, processed and implemented by the respective targets. This effect is aggravated by the fact that delays are added between levels, meaning that set-points are received in the LV network well beyond the sample rate. Under these conditions, the control scheme issues set-points that can negatively affect the system response, since a newer set-point can potentially be dispatched in a counterproductive fashion. Furthermore, in this case a higher number of set-points was required to ensure the restoration of the frequency nominal value, since the control system often dispatched control set-points that were outdated.

The discrete load shedding mechanism that compensates for the shortage in power supply inside the isolated MMG is presented in Fig. 5.6.

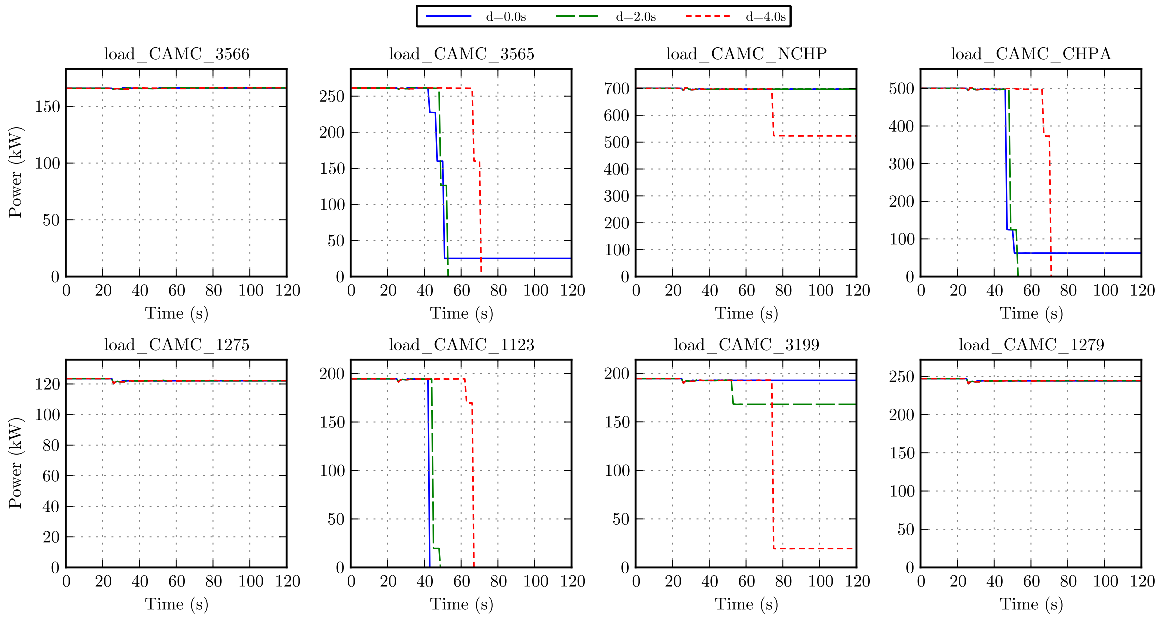



Figure 5.6: MMG MV Load Shedding Scheme in the Presence of Delays

Just a few MV loads are represented to illustrate the discrete nature of the shedding procedure. Only in $d = 4.0$ s case are there significant changes when compared with the case where delays are not considered. It is possible to observe that more loads are shed at $t = 70$ s, which changes the operating conditions for the other remaining participating control entities.

Fig. 5.7 depicts the power output of the MV generators, as consequence of the secondary control decisions. The hydro and diesel units are not centrally controlled and as such no power set-points are issued to them. The impact of communications delays is visible in the presented graphs, although in some cases they are somewhat subtle. The impact when $d = 4.0$ s is however quite visible in the response of the centrally controllable CHPs. As highlighted before, under these conditions, the control scheme is taking decisions prior to the effective reaction to previous set-points, with impacts also in the load shedding process. One of the consequences is a higher load shedding, which due to their discrete nature creates imbalances that need to be corrected by the available generating units. This imbalance is particularly visible at $t = 70$ s in Fig. 5.7, where the abrupt variation in the system frequency triggers the local control of the diesel machine. The response of this machine is due to the frequency deviation that falls outside the droop control dead-band and triggers its primary control. At the same time both CHP units are requested by the central control scheme to reduce their generation output, due to the frequency deviation. In the following control periods CHP take some of the load from CHPA, since it is a cheaper unit to dispatch when compared to CHPA.

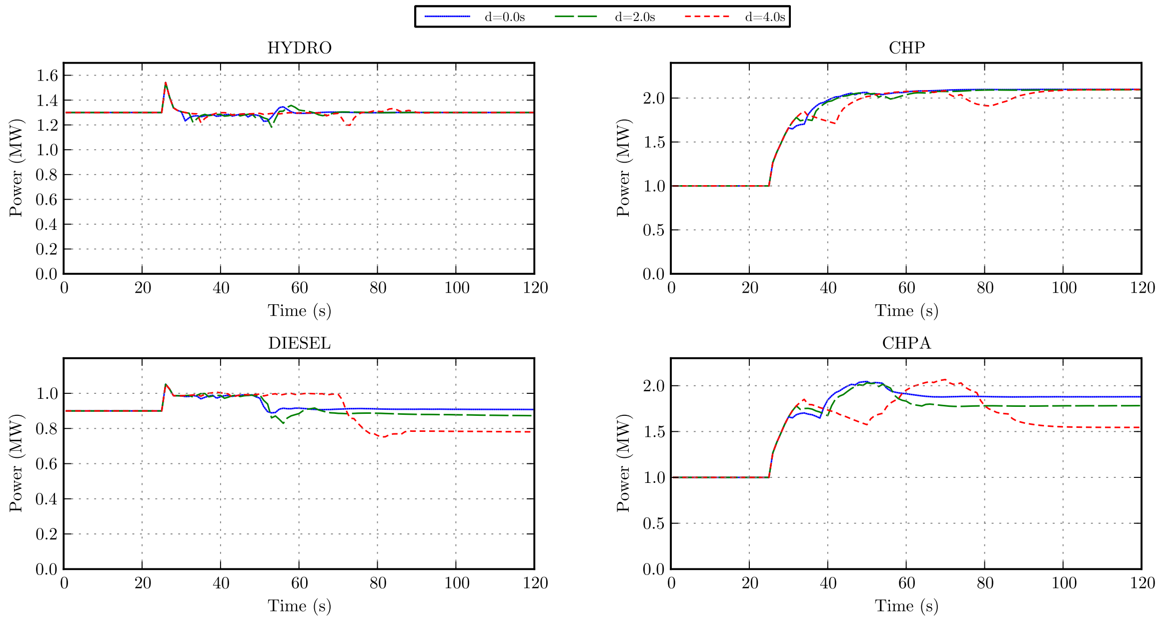



Figure 5.7: MMG MV Generators Response in the Presence of Delays

The response of some of the generating units and aggregated loads inside two controllable microgrids is illustrated in Fig. 5.8.

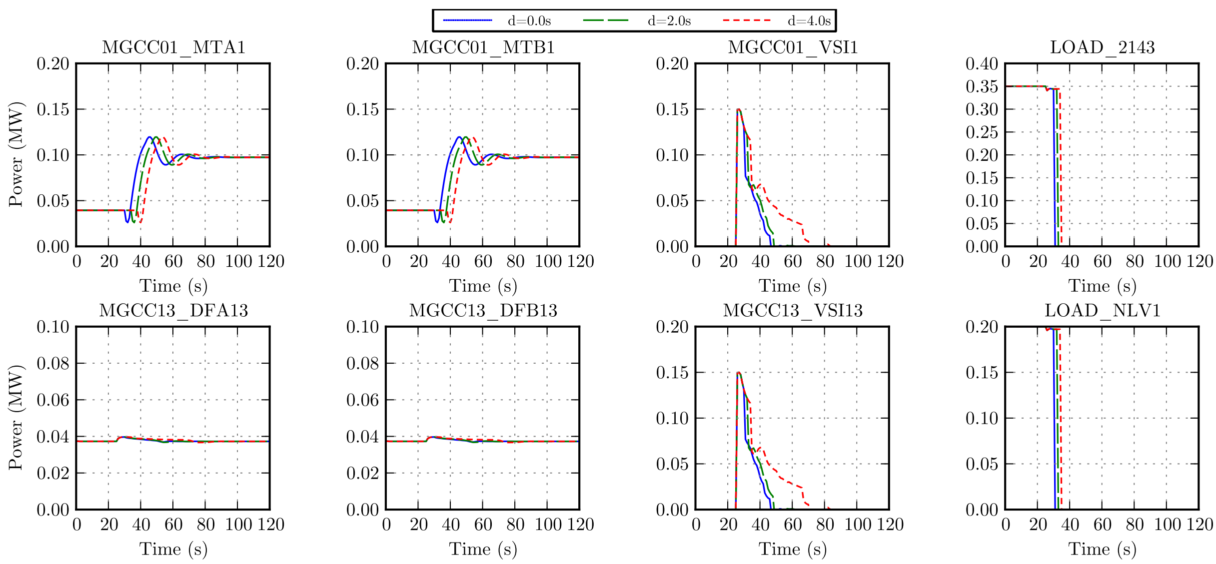
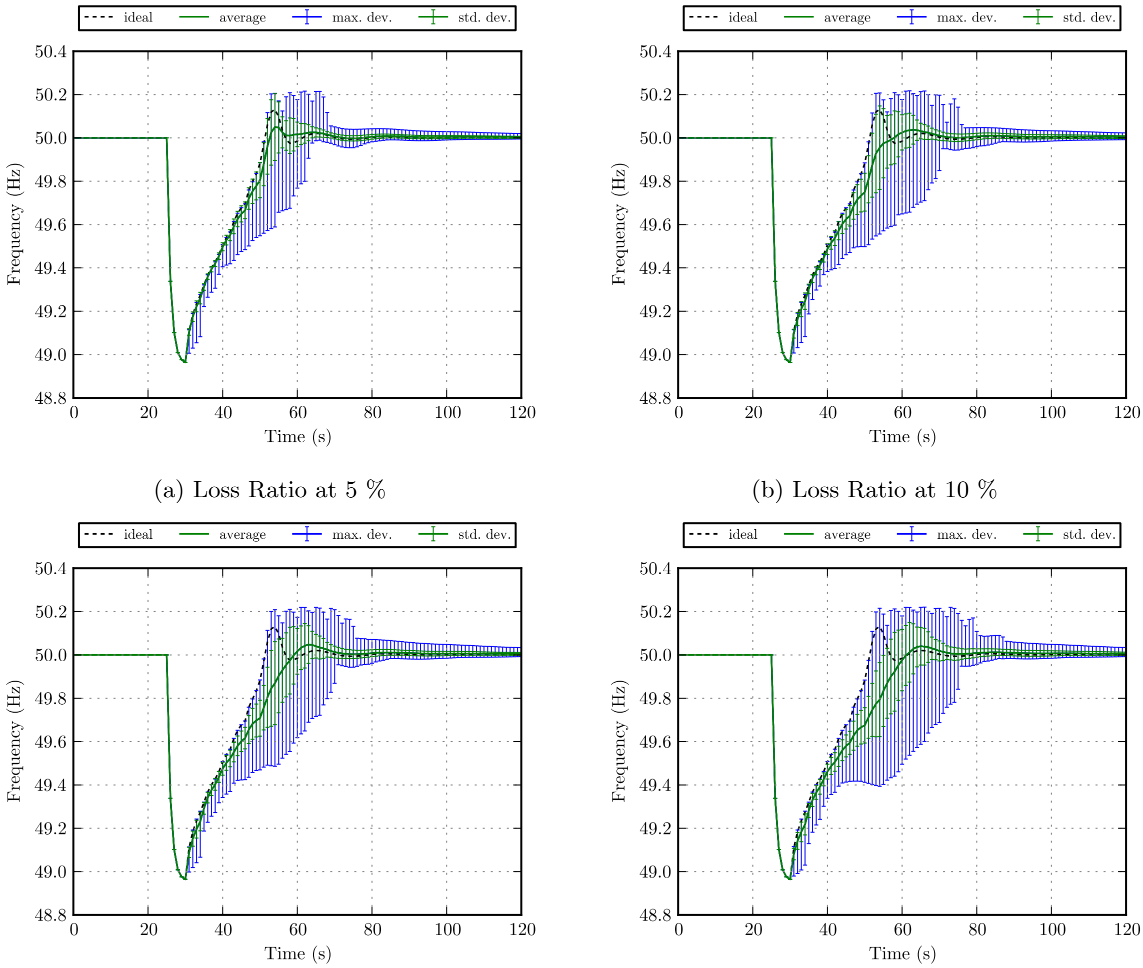



Figure 5.8: MG Generators and Load Response in the Presence of Delays

They have different characteristics, namely in terms of the available generation and load power. As mentioned before, only microturbines (MTA and MTB) and loads are centrally controllable. The VSI response is associated with its primary frequency control scheme in supporting the grid operation after the isolation event. VSIs are expected to be disconnected after the MMG control scheme is able to handle the disturbance conveniently by dispatching alternative generators to compensate for. The PVs and the micro wind generators (DFA and DFB) are not centrally controlled due to the variable nature of the primary energy source. Existing fuel cells are also considered to be not controllable due to their typical slow response time [4]. The impact of the different delay values is visible in the delayed response of each of the microturbines. They are also visible in the amount of time the VSI is required to inject power to support the grid operation. When $d = 4.0$ s due to the previously mentioned constraints in the control scheme, the VSI contribution is visibly higher.




(a) Loss Ratio at 5 %
(b) Loss Ratio at 10 %
(c) Loss Ratio at 15 %
(d) Loss Ratio at 20 %

Figure 5.9: MMG System Frequency Response in the Presence of Losses

Similarly, an evaluation of the impact of set-points exchanged within the control actions associated with the secondary control was conducted when in the presence of data loss. As such, a set of predefined loss ratio values were defined, generically for all the set-points exchanged within the MMG, meaning that each set-point exchange has the same probability of being lost for a predefined loss ratio value. When set-points are lost no data retransmission is considered due to the counterproductive effect of exchanging outdated set-points, as it so happened when delays were excessive. Given the diversity of set-points that can be affected by the data loss, a Monte Carlo simulation method was implemented. This allows a convenient way of evaluating the previously mentioned impacts, since they can affect different targets at different time intervals of the centralized control scheme. A set of 1000 simulation runs was conducted for different loss ratio target values and the results are presented in Fig. 5.9.

In each of the considered cases, where the average loss ratio is varied between 5% and 20%, the ideal system response is presented, where no losses occur, which is illustrated by a black dashed line. The average system frequency represented in full and in green provides an overall perspective of the impact of losses in the control scheme in the system response. The represented standard deviation and the maximum upper and lower deviations allow the perception of the dispersion from the average and extreme deviations.

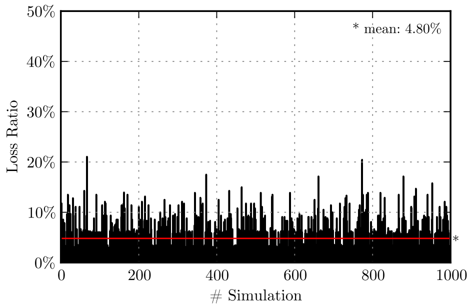
In all cases, the average curves of the system frequency show a delayed response when compared to the ideal case. Another visible aspect is the fact that the ideal case bounds the upper deviations up from the average curve, until the overshoot is reached, making it in fact the fastest and ideal response possible, since there are no losses. The maximum deviations show that the system response is mostly affected when the control scheme is trying to balance the increase in power generation with the necessary load shedding procedure. This phenomenon is expected since the loss of set-points means that there is an amount of power that has to be compensated in the next control time step. As expected, for higher loss ratio values the average response delay is also higher. The same reasoning is applicable to both standard and maximum deviation, that also grow with higher loss ratios.

The loss ratio values for each simulation run of the Monte Carlo implementation are presented in Fig. 5.10. The line in full represents the average value of the loss ratio that was achieved in each set of M-C simulations. In general the values are coherent with the target loss ratio values set at the beginning of each simulation run. On one hand it should be noted that a limited number of set-points is exchanged in each control time step, which can introduce significant variations in the actual loss ratio of each run of the M-C simulation. On the other hand this visible variability of the loss ratio in each simulation run allowed the necessary variation in terms of frequency response in order to evaluate the effectiveness of the control scheme when in the presence of information loss uncertainty, as depicted in Fig. 5.9.

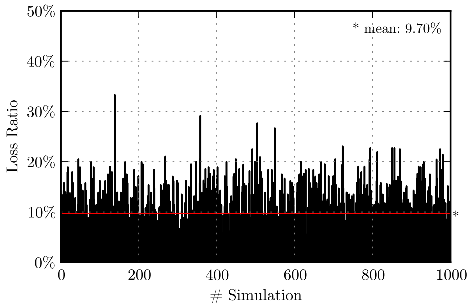
## 5.3 Characterization of Distribution Feeders

In previous chapters it was emphasized the importance of a geographical perception of the distribution feeders. This information allows a better characterization of the context upon which communications systems are set to support the necessary exchange of data among nodes participating in different smart grid applications and in different scenarios.

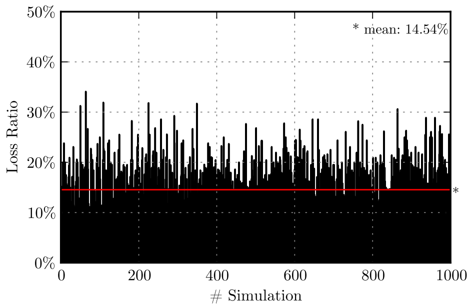
In this section a geographic characterization of Portuguese distribution feeders is presented, with the purpose of evaluating the geographic context where communications technologies will have to be deployed. The data considered here was provided anonymously by the Portuguese distribution system



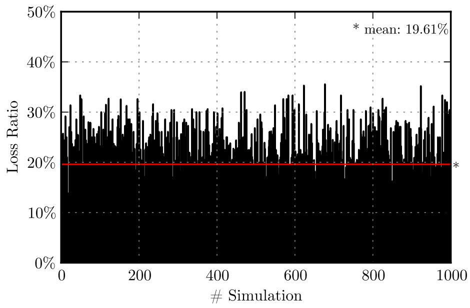

(a) For a Target Loss Ratio of 5 %




(b) For a Target Loss Ratio of 10 %




(c) For a Target Loss Ratio of 15 %




(d) For a Target Loss Ratio of 20 %

Figure 5.10: Loss Ratio per Simulation Run

operator, EDPD, and contains information regarding both LV and MV feeders pertaining to different scenarios. As such, a set of bulk data concerning several distribution feeders was analyzed, from which relevant information geographic information was extracted. Among others, it was possible to know: the number of lines fed by each substation (HV/MV and MV/LV); the number of customers; the electric line distance between nodes and between each node and the serving substation; the direct distance between nodes and between each node and the serving substation; the distance of each node to the nearest neighbor in terms of electric line or direct path; and the number of ramifications and derivations for each electric line, from the serving substation to each end customer premises.

In Appendix D a geographical representation of some of the considered types of feeders is anonymously presented, allowing a better understanding of the physical topology of each feeder, the respective node distribution for the LV and MV electric networks and a general idea of the involved distances.

As will be shown from the conducted data analysis, the main objective of this work was to find a probability distribution that is able to accurately represent the placement of nodes that are part of the electric distribution network, like substations and end customers premises, which are also potentially communicating nodes within the last-mile segment. This data can then be used to randomly generate scenarios with different positioning of nodes allowing the assessment and evaluation of potential communications solutions at a later stage, while considering some diversity in terms of node placement. To that end a set of goodness of fit tests, which include the probability distribution parameter estimation, were carried out using MATLAB® distribution fitting tools over the samples extracted from the previously mentioned set of provided data.

The analyzed scenarios are divided into LV and MV distribution networks and a previous classification of data is established in order to simplify the analysis, by defining the target scenarios to be considered: urban, mixed and urban. The selected classes for both LV and MV electric networks are: rural, mixed and urban. For the purpose of the following analysis the main differences between them are the average number of nodes and the involved distances among neighboring nodes.

### 5.3.1 LV Distribution Networks

From the provided information five types of LV feeders were already established as being representative of the Portuguese LV distribution network. Each type represents a typical feeder associated with a specific secondary substation rated power, representing a range of rural and urban scenarios. The following classification in terms of power, size and location was hence established from the available data:

- Small rural - 50 kVA
- Medium Rural - 100 kVA
- Large Rural - 160 to 250 kVA
- Urban Outskirts - 400 kVA
- Urban Center - 630 kVA

Fig. 5.11 illustrates the distribution, expressed as a percentage, of the number of customers associated with each secondary substation power class for the Portuguese network.

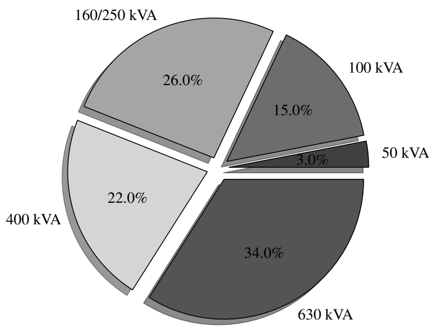



Figure 5.11: LV Customer Distribution

It is noticeable that the number of customers in urban and rural scenarios is similar, representing respectively 56% and 44% of the total number of customers. The class with the highest customer density is the 630 kVA, which represents 34% of the total, whereas the 50 kVA only represents 3% of the total LV customers. Data suggests that the concentration of customers is higher in urban scenarios, as expected. Table 5.1 shows the average number of single-phase and three-phase customers along with the average length of both underground and overhead electric lines, for each feeder class, is presented. As mentioned previously three main scenarios were established. In the rural scenario data from 50 and 100 kVA feeders was considered, in the mixed scenario data from 160/250 kVA and 400 kVA feeders was used, which left the 630 kVA feeder as the source for the urban scenario case. With this classification a set of tests of hypothesis was conducted for each of these scenarios, to evaluate the goodness of fit of different probability distributions. Given the variability in the Chi-Square test results, mentioned in the previous chapter, only the Kolmogorov-Smirnov (K-S) and the Anderson-Darling (A-D) tests were considered to decide on the candidate distributions in each scenario.

Table 5.1: Characteristics LV Feeders

| **Characteristics** | **Power Class (kVA)** | | | | |
|---|---|---|---|---|---|
| | 50 | 100 | 160/250 | 400 | 630 |
| # single-phase customers | 18 | 39 | 62 | 105 | 125 |
| # three-phase customers | 4 | 12 | 26 | 37 | 50 |
| # total customers | 22 | 51 | 88 | 142 | 175 |
| Overhead line length (m) | 2024 | 2035 | 2055 | 1940 | 593 |
| Underground line length (m) | 0 | 58 | 127 | 366 | 1589 |
| Total length (m) | 2024 | 2093 | 2182 | 2306 | 2182 |

Table 5.2 presents the results of the tests of hypothesis for the LV rural scenario. Generically, all distributions except the exponential are deemed proper to represent the sample data. The respective QQ-plot, presented in Fig. 5.12, shows how close are the quantiles of the probability distributions and the quantiles of the sample data.

Table 5.2: Hypothesis Test for the LV Rural Scenario

| **Probability Distribution** | Kolmogorov-Smirnov | | Anderson-Darling | |
|---|---|---|---|---|
| | $\alpha$=0.01 | $\alpha$=0.05 | $\alpha$=0.01 | $\alpha$=0.05 |
| Burr | *not reject* | *not reject* | *not reject* | *not reject* |
| Exponential | *not reject* | reject | reject | reject |
| Gamma | *not reject* | *not reject* | *not reject* | *not reject* |
| Gen. Pareto | *not reject* | *not reject* | *not reject* | *not reject* |
| Log-Normal | *not reject* | *not reject* | *not reject* | *not reject* |
| Weibull | *not reject* | *not reject* | *not reject* | *not reject* |

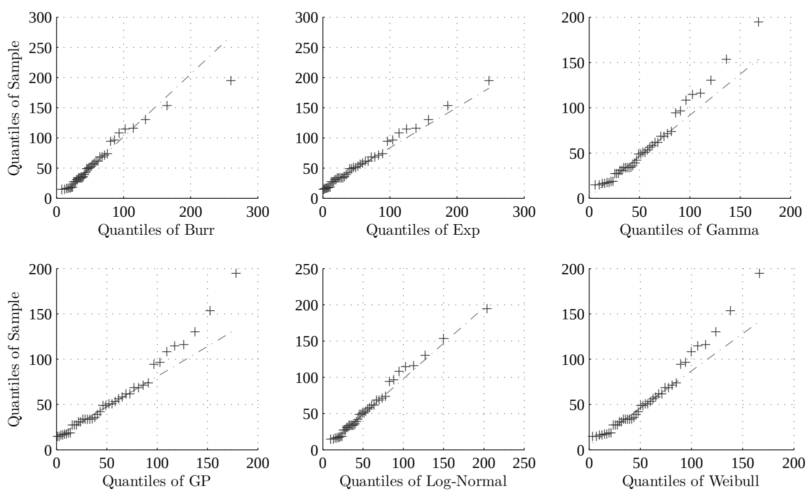



Figure 5.12: LV Rural Scenario QQ-Plot

Although the QQ-plot only introduces a visual confirmation, it can nonetheless be used to select a probability distribution based on a proximity criterion of both data central points and outliers. The plotted dashed line joins the first and third quantiles of the distribution and it is extrapolated to the remaining points. It provides a linear fit of the order statistics of both samples, that is the linearity of the data under evaluation and the deviation from the $y = x$ line.

The same procedure was carried out for the mixed scenario and Table 5.3 shows the results of the same tests of hypothesis for each probability distribution. The Burr, Gamma and Log-Normal distributions are not rejected by any of the tests, making them suitable and potential candidates. The Weibull distribution can also be considered, in case the tail values are not important, since the K-S test does not reject the central points but the A-D test fails in accepting it as a representation of extreme values.

Table 5.3: Hypothesis Test for the LV Mixed Scenario

| **Probability Distribution** | Kolmogorov-Smirnov | | Anderson-Darling | |
|---|---|---|---|---|
| | $\alpha$=0.01 | $\alpha$=0.05 | $\alpha$=0.01 | $\alpha$=0.05 |
| Burr | *not reject* | *not reject* | *not reject* | *not reject* |
| Exponential | reject | reject | reject | reject |
| Gamma | *not reject* | *not reject* | *not reject* | *not reject* |
| Gen. Pareto | reject | reject | reject | reject |
| Log-Normal | *not reject* | *not reject* | *not reject* | *not reject* |
| Weibull | *not reject* | *not reject* | reject | reject |

The respective QQ-plot, presented in Fig. 5.13, shows small deviation in all three probability distributions, being the differences mainly the proximity to different groups of values. Despite the potential visual inaccuracy when interpreting the QQ-plot, the Gamma distribution seems to represent better the data sample central points, whereas the Burr and Log-Normal distributions show smaller differences between the quantiles, for the extreme values.

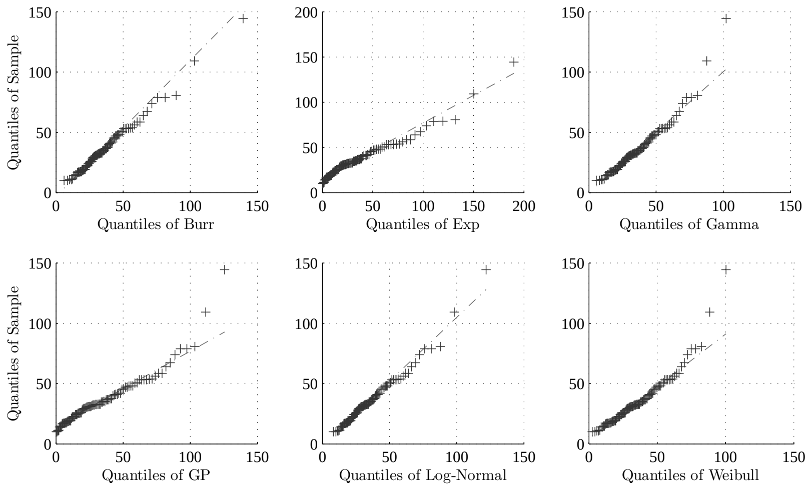



Figure 5.13: LV Mixed Scenario QQ-Plot

Table 5.4 presents the results of the tests of hypothesis for the urban scenario. The Burr probability distribution is the only one that is not rejected by any of the tests, which suggests its better capability in representing the sample data. In case the extreme values are not considered, the Log-Normal distribution offers a suitable proximity for the central values, since the K-S test does not reject at any of the significance levels.

Table 5.4: Hypothesis Test for the LV Urban Scenario

| **Probability Distribution** | Kolmogorov-Smirnov | | Anderson-Darling | |
|---|---|---|---|---|
| | $\alpha$=0.01 | $\alpha$=0.05 | $\alpha$=0.01 | $\alpha$=0.05 |
| Burr | *not reject* | *not reject* | *not reject* | *not reject* |
| Exponential | reject | reject | reject | reject |
| Gamma | *not reject* | reject | *not reject* | reject |
| Gen. Pareto | reject | reject | reject | reject |
| Log-Normal | *not reject* | *not reject* | reject | reject |
| Weibull | *not reject* | reject | reject | reject |

Unlike in the previous case the QQ-plots, presented in Fig. 5.14, show the presence of outliers with significant deviations for all the probability distributions. Although the hypothesis tests suggest the Burr distribution as a potential candidate since it is not rejected, it cannot be ignored the fact that for extreme values the representation of the sample will likely be distorted. Nonetheless the remaining quantile points are, in general, close and show a consistent proximity to the straight line.

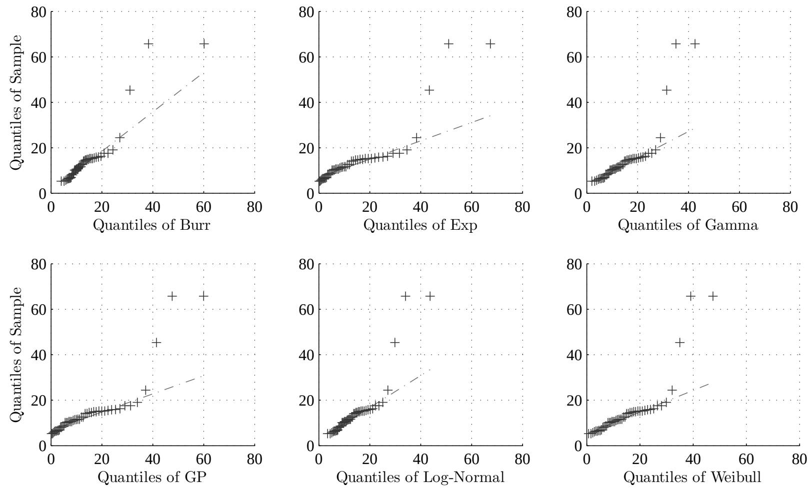



Figure 5.14: LV Urban Scenario QQ-Plot

### 5.3.2 MV Distribution Networks

Similarly to the previous subsection, data samples from MV feeders were also analyzed in order to provide a geographic characterization of some of the Portuguese MV distribution networks. A similar classification was also established with urban, mixed and rural scenarios being considered. In the rural scenario only MV feeders from rural areas are considered. Conversely, in the urban scenario only feeders installed in urban environments are taken into consideration. The mixed scenario was created from MV feeders that include both urban and rural environments. An illustration of the MV feeders considered for this analysis is presented in section D.2 of Appendix D.

Table 5.5 presents the results from the conducted hypothesis test, where the Burr and Gamma probability distributions are the only potential candidates in representing the sample data associated with rural MV feeders since no rejection occurs.

Table 5.5: Hypothesis Test for the MV Rural Scenario

| **Probability Distribution** | Kolmogorov-Smirnov | | Anderson-Darling | |
|---|---|---|---|---|
| | $\alpha$=0.01 | $\alpha$=0.05 | $\alpha$=0.01 | $\alpha$=0.05 |
| Burr | *not reject* | *not reject* | *not reject* | *not reject* |
| Exponential | *not reject* | reject | reject | reject |
| Gamma | *not reject* | *not reject* | *not reject* | *not reject* |
| Gen. Pareto | *not reject* | reject | *not reject* | reject |
| Log-Normal | *not reject* | *not reject* | reject | reject |
| Weibull | *not reject* | *not reject* | reject | reject |

The QQ-plot presented in Fig. 5.15 shows that in fact the Burr and Gamma distributions have the quantile points closer to the straight line, without significant deviations.

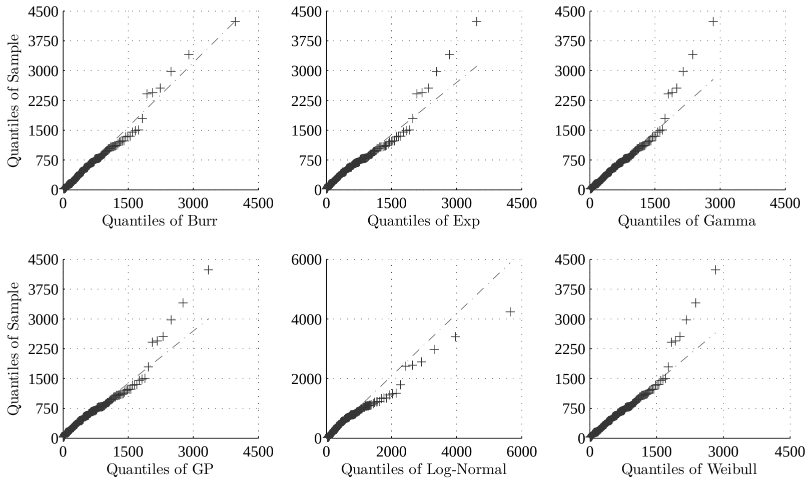



Figure 5.15: MV Rural Scenario QQ-Plot

Table 5.6 shows that the Burr probability distribution is the only one that is not rejected by the K-S and A-D tests of hypothesis as a suitable representation of the data sample from a mixed MV network. Analytically, it is the most suited probability distribution to represent the data and besides the Log-Normal that passes the K-S test, all other hypothesis are rejected and discarded as candidates.

Table 5.6: Hypothesis Test for the MV Mixed Scenario

| **Probability Distribution** | Kolmogorov-Smirnov | | Anderson-Darling | |
|---|---|---|---|---|
| | $\alpha$=0.01 | $\alpha$=0.05 | $\alpha$=0.01 | $\alpha$=0.05 |
| Burr | *not reject* | *not reject* | *not reject* | *not reject* |
| Exponential | reject | reject | reject | reject |
| Gamma | reject | reject | reject | reject |
| Gen. Pareto | reject | reject | reject | reject |
| Log-Normal | *not reject* | *not reject* | *not reject* | reject |
| Weibull | reject | reject | reject | reject |

The respective QQ-plot, presented in Fig. 5.16, shows that despite the non-rejection of the K-S and A-D tests there is a significant number of points clearly outside the straight line. This suggests once more that the representation of the extreme quantile points will not be accurate. Moreover it is difficult to decide on the Burr distribution as the only candidate since like the other it also presents visible deviations in the extreme values.

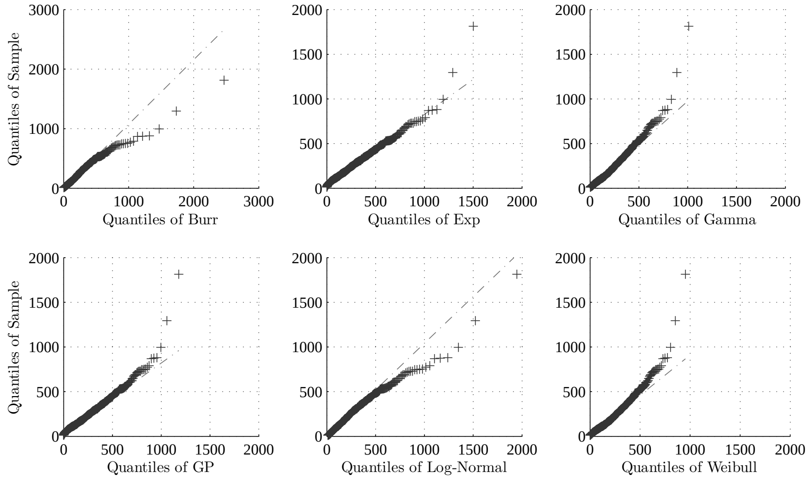



Figure 5.16: MV Mixed Scenario QQ-Plot

From Table 5.7 there is no candidate to represent the data associated with the MV urban scenario, that is not rejected by any of the K-S and A-D tests at different significance levels. On one hand the Log-Normal and the Weibull distributions are not rejected by the K-S test, which suggests their suitability for representing points from the data sample closer to the center. On the other hand the Burr and Gamma distributions are not rejected by the A-D test, despite the significance level, and are only rejected by the K-S test for $\alpha = 0.5$. This makes them suitable for representing extreme values as well as those near the center.

Table 5.7: Hypothesis Test for the MV Urban Scenario

| **Probability Distribution** | Kolmogorov-Smirnov | | Anderson-Darling | |
|---|---|---|---|---|
| | $\alpha$=0.01 | $\alpha$=0.05 | $\alpha$=0.01 | $\alpha$=0.05 |
| Burr | *not reject* | reject | *not reject* | *not reject* |
| Exponential | reject | reject | reject | reject |
| Gamma | *not reject* | reject | *not reject* | *not reject* |
| Gen. Pareto | reject | reject | reject | reject |
| Log-Normal | *not reject* | *not reject* | reject | reject |
| Weibull | *not reject* | *not reject* | reject | reject |

The QQ-plot presented in Fig. 5.17 shows that the mentioned candidates have the lower quantile values near the straight line and that the Burr and Log-Normal distributions show a good compromise also at higher quantile values.

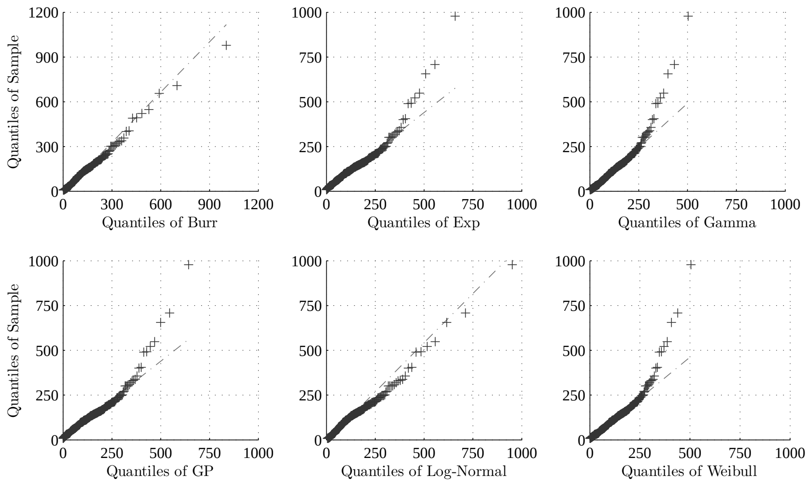



Figure 5.17: MV Urban Scenario QQ-Plot

### 5.3.3 Parameters of Probability Distributions

Despite the limitations in finding a PDF that accurately describes each of the considered scenarios it should be noted that the main objective is to use random generators to create some diversity in the node positioning. This will be used in Section 5.4 where a random scenarios generator tool is presented to enable a comprehensive assessment of the performance of WMNs considering the characteristics of each type of distribution network. As such, a selection of the probability distributions for each case must be made, to allow its use in generating different node positions for each of the considered scenarios. Hence, for each distribution it is necessary to estimate its parameters and establish from the available data the number of potentially communicating nodes in each type of electric network. A summary of the selected distributions for each LV and MV scenarios is presented in Table 5.8, along with the respective parameters and associated number of communicating nodes.

Table 5.8: Scenarios and Respective Probability Distributions Parameters

| | **Scenario** | **Prob. Distr.** | **Parameters** | **Avg. Comm. Nodes** | **Avg. Agg. Nodes** |
|---|---|---|---|---|---|
| **LV** | Rural | Burr | $\alpha \approx 42.88$, $c \approx 2.56$, $k \approx 0.96$ | 49 | 72 |
| | Mixed | Gamma | $\alpha \approx 3.68$, $\beta \approx 9.84$ | 111 | 232 |
| | Urban | Burr | $\alpha \approx 9.40$, $c \approx 4.53$, $k \approx 0.54$ | 51 | 256 |
| **MV** | Rural | Burr | $\alpha \approx 953.19$, $c \approx 1.51$, $k \approx 2.67$ | 105 | 49 |
| | Mixed | Burr | $\alpha \approx 205.94$, $c \approx 1.96$, $k \approx 1.61$ | 218 | 111 |
| | Urban | Burr | $\alpha \approx 109.73$, $c \approx 1.72$, $k \approx 1.83$ | 59 | 51 |

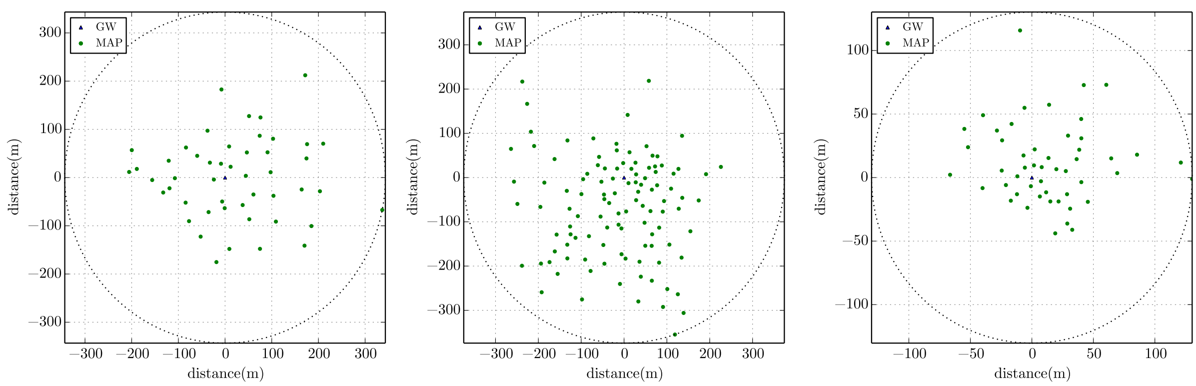
The penultimate column contains the number of communications nodes that need to exchange information in each type of scenario. For a MV network this value includes a HV/MV substation and the associated secondary MV/LV substations, whereas in a LV network it includes the secondary substation and buildings where end consumers are served. The last column contains the number of downstream aggregated nodes served by each communications nodes. In a MV network this represents the average aggregated number of nodes with which the secondary substations exchange data. In LV networks this represents the average number of end consumers associated with each building. In both cases this value characterizes the density of aggregated nodes and consequently the potential data traffic. As expected this value is lower in rural and higher in urban scenarios.

## 5.4 Wireless Mesh Networks for Last-Mile Communications

This section approaches the use of WMNs in the scope of smart grids as a potential solution in supporting a last-mile communications infrastructure that is able to cope with the control schemes discussed so far. A set of scenarios was defined based on the geographic characterization and probability distribution candidates that were assessed in the previous section. An evaluation of a WMN based on WiFIX follows with the analysis of the network requirements in terms of communicating nodes to ensure a proper coverage of each of the considered scenarios are evaluated along with the network performance in terms of delays and information losses.

### 5.4.1 Distribution Grid Scenarios

A set of distribution network types have been established in previous sections and a set of PDFs have been assessed to provide the basis for random generators to be used in the definition of different distribution grids that allow exploring the impact of the variability of node placement, under different contexts, in the performance a WMN based on WiFIX. In Fig. 5.18 a random generation of node positions for each type of LV scenario is illustrated. The node positioning and involved distances between nodes, represented in meters, are in accordance with the graphic representation of feeders presented in Appendix D.

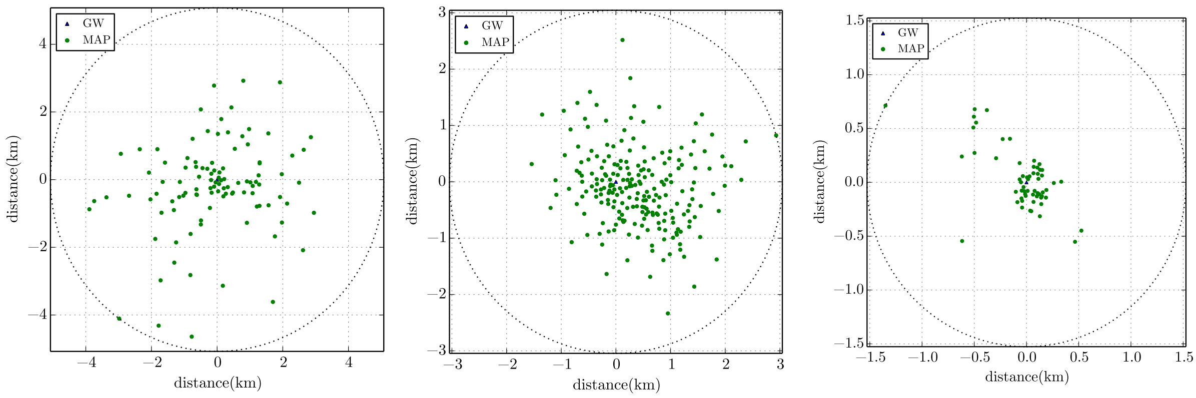



(a) Rural (b) Mixed (c) Urban

Figure 5.18: LV Scenarios

The GW node is always located at the center (0,0); in MV scenarios it represents a HV/MV substation whereas in LV it represents a MV/LV secondary substation with which all remaining nodes exchange data. The dashed circle signals the farthest MAP node from the GW, thus illustrating the geographic span of the communications network.

Similarly in Fig. 5.19 a random generation of node positions for each type of MV scenario is portrayed. A set of randomly generated scenarios can hence be used to evaluate the performance of WiFIX using a Monte Carlo implementation, once the connectivity among all communicating nodes is ensured.

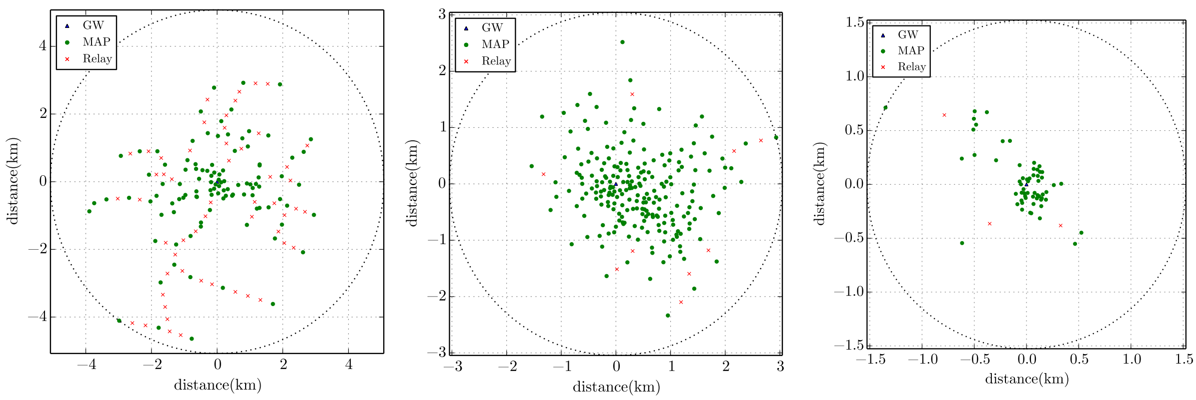



(a) Rural (b) Mixed (c) Urban

Figure 5.19: MV Scenarios

### 5.4.2 WiFIX in Last-Mile Communications Scenarios

For each of the generated scenarios it is necessary to deploy a WiFIX wireless mesh network. The nodes from the previously generated scenarios are also communicating nodes of the WiFIX network, Mesh Access Points (MAP), but since the involved distances may leave some MAPs without connectivity, relay nodes have to be added. Unlike MAPs these relay nodes do not generate traffic and are only responsible for relaying information from and to a GW node. The ns-3 WiFIX module processes the different scenarios and, according to the propagation characteristics, establishes the number and position of the relay nodes if they have to be added.




(a) Rural (b) Mixed (c) Urban

Figure 5.20: MV Scenarios With Relay Placement

In all cases of the considered LV scenarios no relays were necessary to ensure the coverage of all MAPs. As it will be shown, the installed MAPs are able to exchange data directly with the GW node. Conversely in the MV networks a significant amount of cases requires relays to be added due to the involved distances. Fig. 5.20 illustrates the placement of relay nodes for a single case of each of the MV scenarios presented earlier in Fig. 5.19.

The average number of relays necessary for each case of the Monte Carlo simulation for the MV Rural scenario is shown in Fig. 5.21. It is possible to observe that the number of relays to be installed can vary significantly from 36 to 91 relays. This is due to the varying distances between neighboring nodes. On average, as illustrate by the red line in Fig. 5.21, about 61 relays are needed to ensure the coverage in each of the MV rural cases.

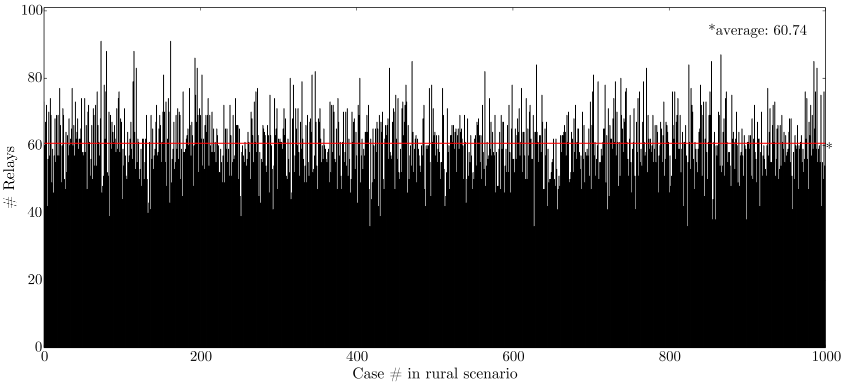



Figure 5.21: MV Rural - Number of Installed Relays

The number of installed relays for the each of the simulated cases of the MV Mixed scenario is represented in Fig. 5.22.

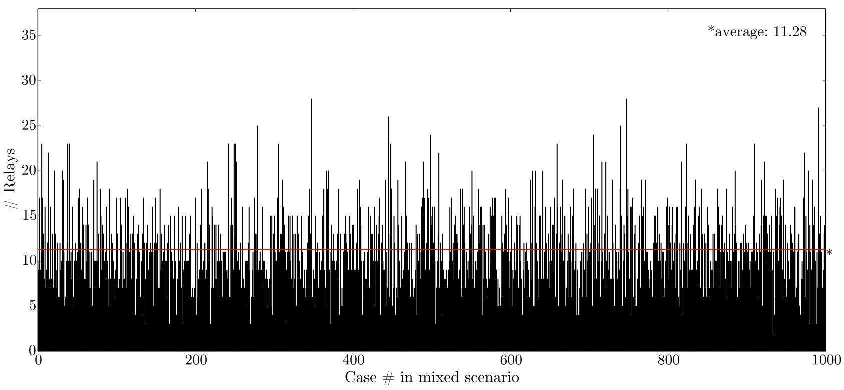



Figure 5.22: MV Mixed - Number of Installed Relays

Despite the higher number of MAP nodes when compared with the rural counterpart, the smaller distances between neighboring MAP nodes means that less relays have to be installed. Hence, more MAPs are able to forward information among them without needing relays to overcome the established

RF distance between nodes. There is also a significant variation on the number of installed relays for each case, which ranges between 2 and 28. On average about 11 relays are necessary to ensure connectivity in each case.

Fig. 5.23 depicts the average number of relays installed in the MV Urban scenario. In most cases no relays are necessary to ensure the coverage, since in general the position and distance between MAPs allow them to forward information without relays. The number of relays to be installed varies from 0 to 3.

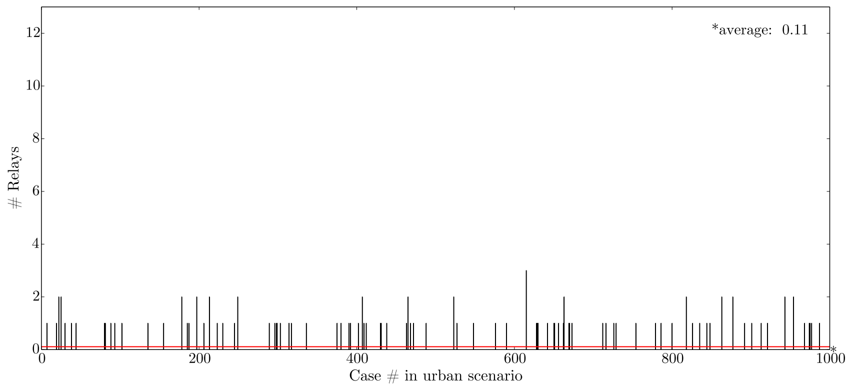



Figure 5.23: MV Urban - Number of Installed Relays

The main ns-3 simulation parameters used throughout this section are presented in Table 5.9. The number of nodes considered for each scenario was previously defined in Table 5.8. It should be mentioned that a few changes were introduced to the underlying IEEE 802.11g to make it compatible with its use outside buildings. Hence the frequency was reduced to 900 MHz and the data rate was assumed to be between 6 and 54 Mbps. Although this means a non-compliance with the IEEE 802.11g standard the objective is to show the compliance of a multi-hop wireless sub-GHz solution with the requirements of smart grids.

Table 5.9: Main Simulation Parameters used in ns-3

| | | | |
|---|---|---|---|
| **Control** | | | |
| RTS/CTS | disabled | | |
| **Radio** | | | |
| TxGain | 5 dB | RxGain | 5 dB |
| TxPowerStart | 16 dBm | TxPowerEnd | 16 dBm |
| EnergyDetectionThreshold | -63 dBm | CCaModelThreshold | -68 dBm |
| Frequency | 900 MHz | Range | 410 m |
| **Models** | | | |
| Propagation | Open Space | Standard | IEEE 802.11g |
| Loss | NIST Error Ratio Model | Mobility | None |
| Antenna height | 1.5 m | Data Rate | [6-54] Mbps |
| **WiFIX** | | | |
| Hello Interval | 10 s | Message Size | 1 kb |
| Warm-up Time | 500 s | Sim Time | Variable (1000 msgs/node) |

The Round Trip Time (RTT) of a complete polling sequence is presented in Fig. 5.24 for each type of LV scenario. It is visible that the RTT is similar for LV rural and urban, respectively ∼56 ms and ∼58 ms on average, since the number of nodes is similar, whereas in the mixed scenario the higher number of nodes has an impact on the also higher RTT, which on average totals ∼127 ms. The scheduling nature of the polling process and the absence of relays in any of the LV scenarios allows the RTT values to be quite stable despite the placement of nodes.

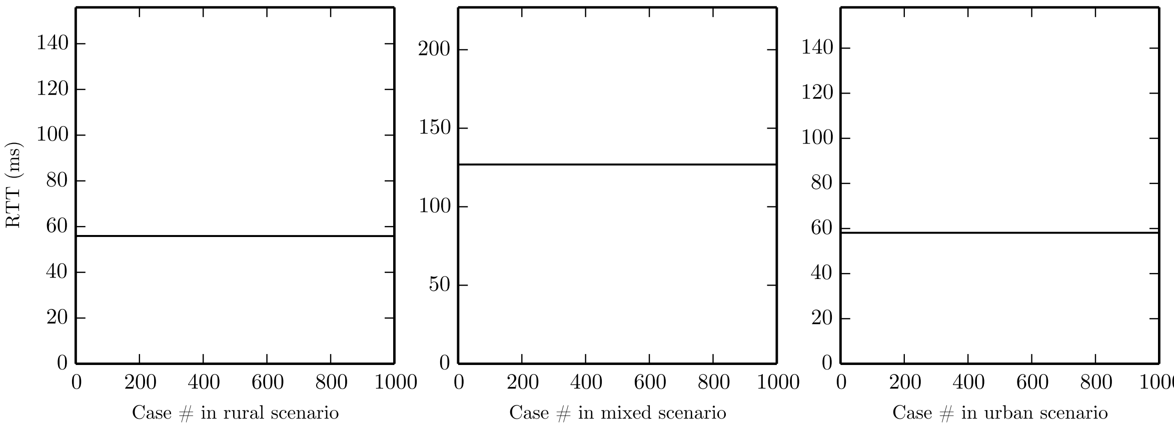



Figure 5.24: RTT in LV scenarios

Similarly, Fig. 5.25 depicts the RTT of the complete polling sequence for each MV scenario. As expected the RTT is lower for the urban scenario where the number of nodes is smaller. The RTT values for the rural and mixed scenarios are visibly close despite the fact that in the latter the number of MAPs is more than the double. This can attributed to the fact that the average number of relays added to the rural scenarios is higher than the number of relays to be installed in the mixed scenario to ensure the necessary connectivity.

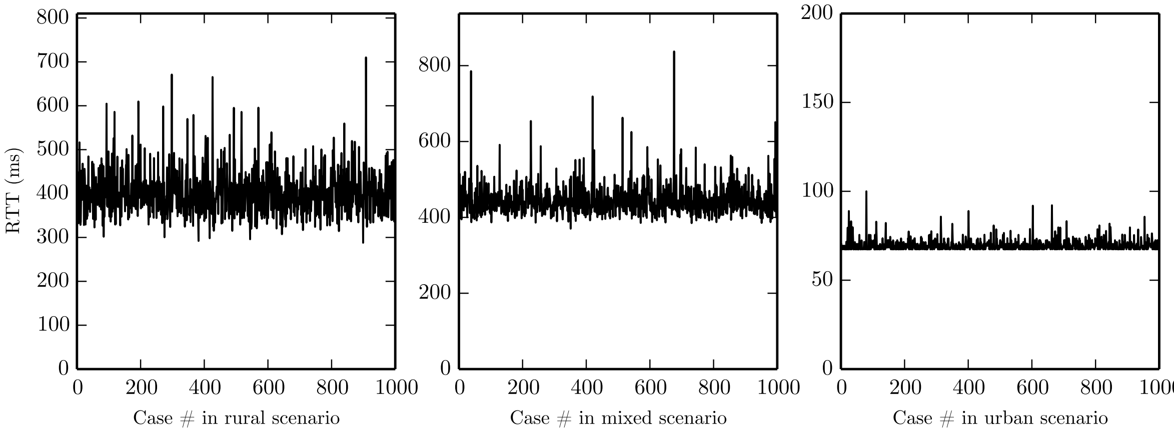



Figure 5.25: RTT in MV scenarios

In terms of throughput Fig. 5.26 presents the achieved values for each type of LV scenario. Since all nodes are within one hop distance there are no noticeable variations in the simulated cases. Like in the RTT the similar number of nodes exchanging data both in rural and urban scenarios means that the throughput is expected to be similar as well. In these cases the average throughput is respectively 568 kbps and 546 kbps, whereas in the mixed case the higher number of nodes has the inverse impact in the lower throughput, which in average is 249 kbps.

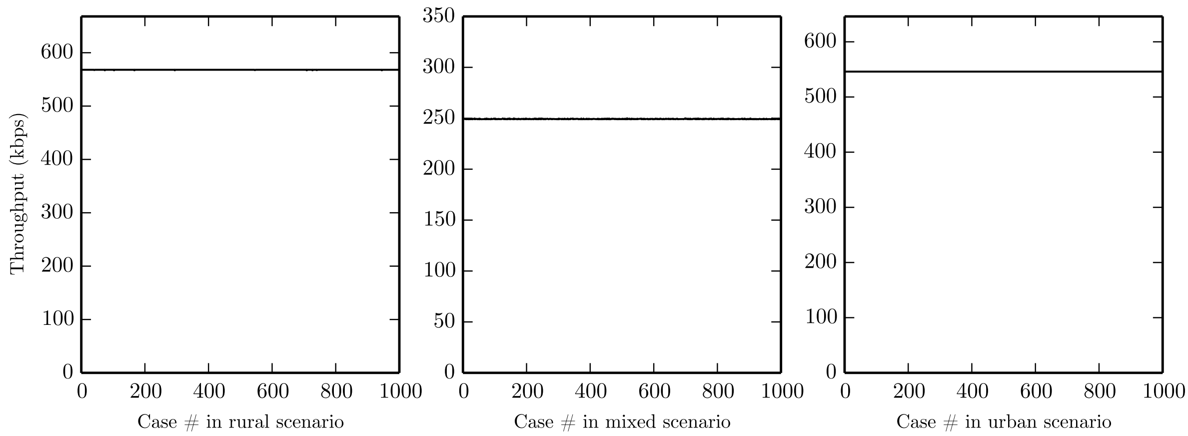



Figure 5.26: Throughput in LV scenarios

The throughput values for the WiFIX networks in the MV scenarios are presented in Fig. 5.27. The presence of relays in theses scenarios has a direct impact on the variation of the throughput. Like in the RTT values presented earlier, in the rural and mixed scenarios the throughput is similar, respectively with 79 kbps and 71 kbps. The variation in the throughput is higher in the rural scenario where the number of relays is also higher when compared with the remaining scenarios but its variation is also higher. In the urban scenario the number of nodes is comparable with the rural and urban LV counterparts and so is the average throughput value, which is 456 kbps.

The previous MV throughput values presented in Fig. 5.27 can be compared with the corresponding expected theoretical values based on the average hop count for each case in each scenario using Eq. 5.1; as depicted in Fig. 5.28 it is possible to see how close are they, namely the variation as a consequence of the average hop count of each case. The $Throughput_{\text{Wi-Fi Link}}$ value represents the throughput associated with a point-to-point connection without contention. The number of nodes, *NumOfNodes*, does not include the relay nodes whereas the *AvgHopCount* depends on the number relays. The same rationale can be applied to the LV scenarios.

$$Throughput = \frac{Throughput_{\text{Wi-Fi Link}}}{AvgHopCount \cdot NumOfNodes} \tag{5.1}$$

Table 5.10 summarizes the results achieved in the different scenarios, where the minimum and maximum hop count values concern the cases where the average hop count is respectively lower and higher in each scenario. The average hop count is the overall mean value of the average hop count of all cases in each scenario.

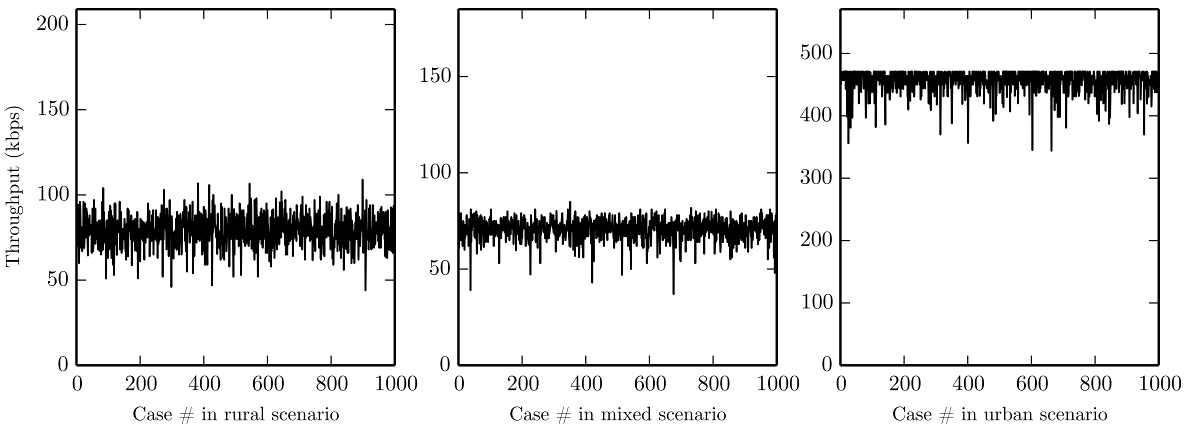



Figure 5.27: Throughput in MV scenarios

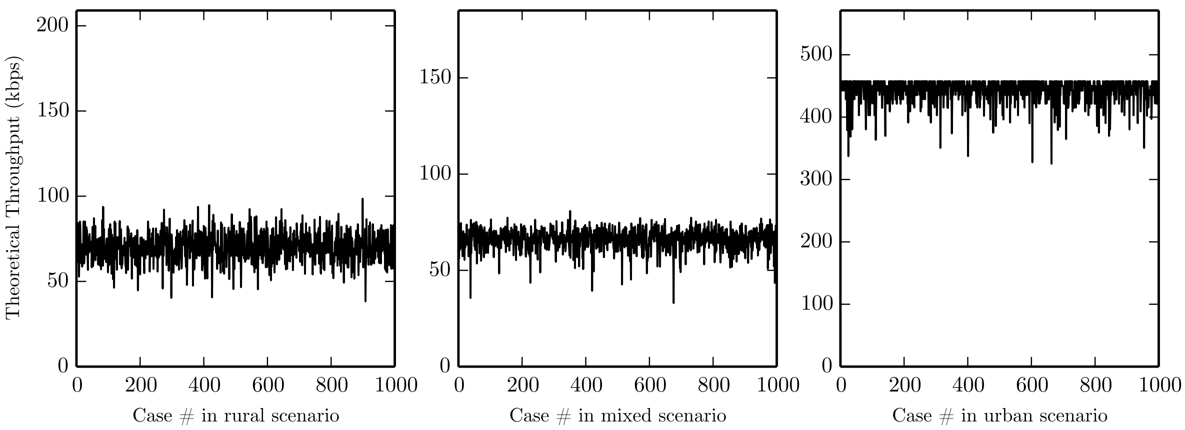



Figure 5.28: Theoretical Throughput in MV scenarios

As mentioned all LV scenarios have no relays and since the hop count is always 1 all nodes are placed within RF range of the GW. A high number of nodes at 1 hop distance from the GW introduced some challenges in the WiFIX logic topology, due to the original limitations on the number of allowable children per node. As such this limitation was removed and WiFIX algorithm was adapted to deal with higher node density within a single-hop. This in turn means that both RTT and throughput value are fairly stable with small differences. In the MV scenarios relays have actually to be added in the majority of cases to ensure the necessary connectivity within the WiFIX network. In the MV urban scenario there is a significant number of cases where no relays were necessary since MAPs were capable of ensuring the connectivity. In these cases there are nodes with direct connectivity with the GW and others that rely on adjacent MAPs to forward data to and from the GW. Since in most cases the average hop count is above 1 it implies that not all nodes are within RF range of the GW. There is however a significant number of cases with very close average hop count, which explains both the throughput upper bound limit and the

Table 5.10: WiFIX ns-3 Simulation Results Summary

| | Scenarios | | | | | |
|---|---|---|---|---|---|---|
| | **LV Rural** | **LV Mixed** | **LV Urban** | **MV Rural** | **MV Mixed** | **MV Urban** |
| **Min relays** | 0 | 0 | 0 | 36 | 2 | 0 |
| **Max relays** | 0 | 0 | 0 | 91 | 28 | 3 |
| **Avg relays** | 0 | 0 | 0 | 60.74 | 11.28 | 0.11 |
| **Avg relays/MAPs ratio** | 0 | 0 | 0 | 0.578 | 0.052 | 0.002 |
| **Min avg hop count** | 1 | 1 | 1 | 2.61 | 1.53 | 1 |
| **Max avg hop count** | 1 | 1 | 1 | 6.71 | 3.74 | 1.41 |
| **Avg hop count** | 1 | 1 | 1 | 3.72 | 1.89 | 1.04 |
| **Min RTT (ms)** | 55.80 | 126.82 | 58.12 | 287.86 | 370.14 | 67.33 |
| **Max RTT (ms)** | 55.91 | 126.97 | 58.17 | 710.23 | 837.43 | 100.01 |
| **Avg RTT (ms)** | 55.84 | 126.89 | 58.14 | 401.61 | 444.86 | 69.62 |
| **Min Throughput (kbps)** | 567.0 | 249.0 | 545.0 | 44.0 | 37.0 | 344.0 |
| **Max Throughput (kbps)** | 568.0 | 250.0 | 547.0 | 109.0 | 85.0 | 471.0 |
| **Avg Throughput (kbps)** | 567.9 | 249.3 | 546.6 | 79.1 | 70.8 | 456.4 |

RTT lower bound limit.

## 5.5 IEEE 1901 Powerline Communications

Powerline communications has been identified previously as a candidate technology to support private networks, allowing the necessary connectivity with end consumers, in the context of last-mile solutions. The difficulties in propagating information in this type of media has raised some concerns in its usage outside the buildings. The propagation and loss models are complex and typically do not address issues related with the actual implementation of the system.

In this section an overview of the error correction schemes employed by the IEEE 1901 is presented and the performance of an IEEE 1901 PHY system is explored. Results presented here are expected to provide an insight on the resilience capabilities of this standard when different SNR values are considered and decoding parameters are configured.

As mentioned in Chapter 4 only part of the IEEE 1901 PHY described in the standard was implemented, along with some simplifications but with a particular concern in trying to incorporate some of the HW limitations typically associated with these systems. Table 5.11 summarizes the main characteristics of the system that will be used in this section and the main configurable parameters.

The implemented encoding/decoding system was subjected to several tests, which included the individual evaluation of separate modules in order to validate the implementation of the different functionalities. Although it is impractical to present all the involved testing procedures it matters to show the validity of some of the modules and their relation with the methodology aspects presented in the previous Chapter. Monte Carlo techniques were extensively used to handle the associated random number generation strategies. The general rule defined in [131] was used, where the minimum number of simulations to be carried out must be higher than the inverse of the number of errors that are to be observed. This means that for an error ratio of $10^{-5}$ at least $10^{5}$ simulations must be carried out.

Results from the mapper module implementation were already illustrated with the graphic representation of the used constellations presented both in Fig. 4.12 and in more detail in Appendix E. The

Table 5.11: IEEE 1901 PHY Simulation Parameters

| Parameter | Values |
|---|---|
| Decoding Algorithm | [BCJR, log-map, max-log-map] |
| Code Rate | ['1/2', '16/21', '16/18'] |
| Modulation Scheme | ['BPSK', 'QPSK', '16-QAM', '64-QAM', '256-QAM'] |
| PHY Blocks | [16, 136, 520] octets |
| SNR | configurable ($E_s/N_0$, $E_b/N_0$) |
| Channel | AWGN |
| Demapper | [soft, hard] / [precise, approximate] |
| Iterations | configurable (num. of turbo decoder iterations) |

demapper module was implemented with a hard and soft bit estimator and the first step is to evaluate the behavior of the hard demapper by comparing its response to the theoretical formulation regarding the Symbol Error Ratio (SER), defined by Eq. 5.2, derived for example from [142].

$$SER \approx \begin{cases} \frac{1}{2}\,\mathrm{erfc}\left(\sqrt{\frac{E_s}{N_0}}\right), \text{for BPSK} \\ 2(1-\frac{1}{\sqrt{M}})\,\mathrm{erfc}\left(n\sqrt{\frac{E_s}{N_0}}\right) - \left(1-\frac{2}{\sqrt{M}}+\frac{1}{M}\right)\mathrm{erfc}\left(n\sqrt{\frac{Es}{N_0}}\right)^2, \text{with } n = \frac{1}{\sqrt{\left(\frac{2}{3}(M-1)\right)}} \text{for M-QAM} \end{cases} \tag{5.2}$$

The theoretical values (<t>) of the SER for each modulation scheme are represented in full in Fig. 5.29. Overlapped are the dashed lines with the simulated (<s>) SER that are achieved using the hard estimation of the demapper. The simulated hard demapping used $10^6$ symbols for each modulation scheme and no encoding on the sequence to be sent over the AWGN channel was performed. The differences between the theoretical and simulated curves for each modulation are due to the inherent approximation of Eq. 5.2 used in the former and the random number generation used in the latter.

A comparison can thus be established between the use of a hard and soft decoding schemes, where in the first no encoding is used and the latter uses a coding rate of '1/2' and the BCJR decoding algorithm with a minimum of 6 turbo iterations. Fig. 5.30 dashed curves represent the SER of the uncoded implementation (<u>) considering the different modulation schemes, whereas the curves in full represent the encoded counterparts (<c>).

On one hand it is visible the considerable gain introduced by the coding scheme in all modulation schemes that were simulated. On the other it is visible the threshold phenomena which is typical in these systems. There is a small $E_s/N_0$ value, below which the SER of the uncoded variants is actually lower than the one achieved by encoded variants. This is due to the accumulation of errors associated with the poor estimates produced by the decoder regarding the received bits, which is aggravated by its recursive nature.

The soft demapping is the foundation for the turbo decoding process carried out by this type of transmission systems. Since two types of soft bit estimation strategies can be associated with the soft decoding module, it matters to understand their impact in the decoding process. Fig. 5.31 represents with full lines the SER for the different modulation schemes when the precise method (<p>) for the soft bit calculation is used, whereas the dashed lines represent the case where an approximation (<a>) is used to calculate the soft bits. Appendix E details the mathematical formulation of both methods. For each

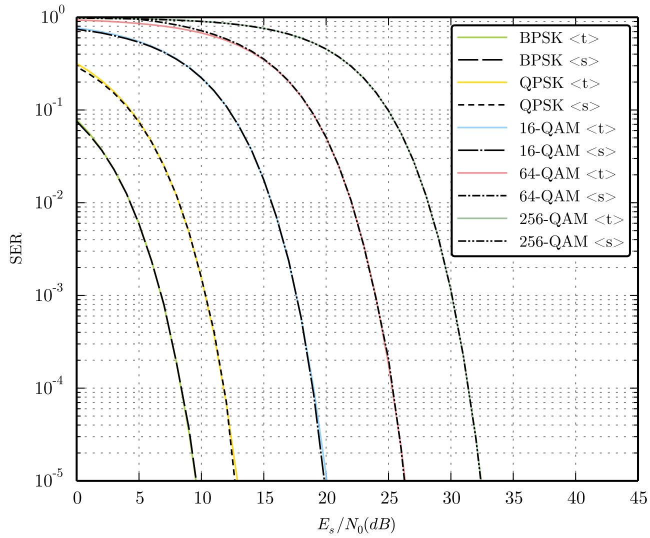



Figure 5.29: Symbol Error Ratio using a Hard Demapper

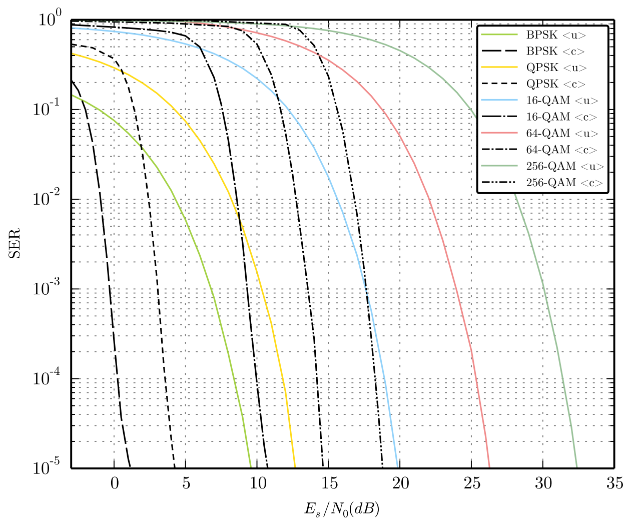



Figure 5.30: Comparison of Uncoded and Coded Implementations

case a PHY Block (PB) of 16 octets was used along with a coding rate of '1/2' and the BCJR decoding algorithm with at least 6 turbo iterations. In all cases $10^6$ simulations were carried out.

There are very small differences, which are somewhat more visible when higher $E_s/N_0$ values are considered, where the approximations in the soft bit calculation slightly degrade the SER curves, but their overall aspect is consistent with the "water-fall" shapes presented earlier. It is however visible a saturation behavior for high $E_s/N_0$ values, which results in the flattening of the SER curves. This is a known phenomenon of convolutional codes, commonly designated by "error floor", which is due to

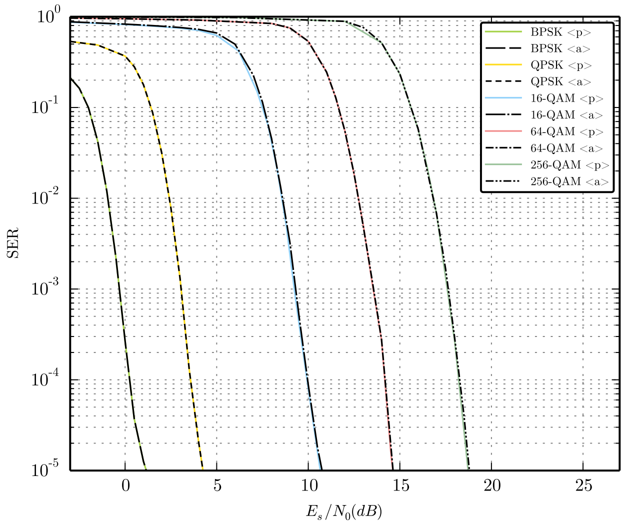



Figure 5.31: Precise and Approximate Soft Bit Calculation

the Hamming weight of the encoded sequences and consequently their free distance [143]. The use of an interleaver in the convolutional encoding scheme, as represented in Fig. 4.8, is shown to reduce the prevalence of low-weight encoded sequences, providing a spectral thinning to mitigate the error flooring [144]. Different calculation strategies can be employed to determine the free distance of the convolutional encoder and thus define a more precise union bound to theoretically represent the error floor, which involves a complex problem to be solved as pointed out in [145]. This phenomenon will become more visible when the number of iterations is evaluated.

A similar comparison can be established between the decoding algorithms that are used in the turbo decoder module. A PB of 16 octets and 5 turbo iterations were used to evaluate each algorithm and the achieved results are depicted in Fig. 5.32.

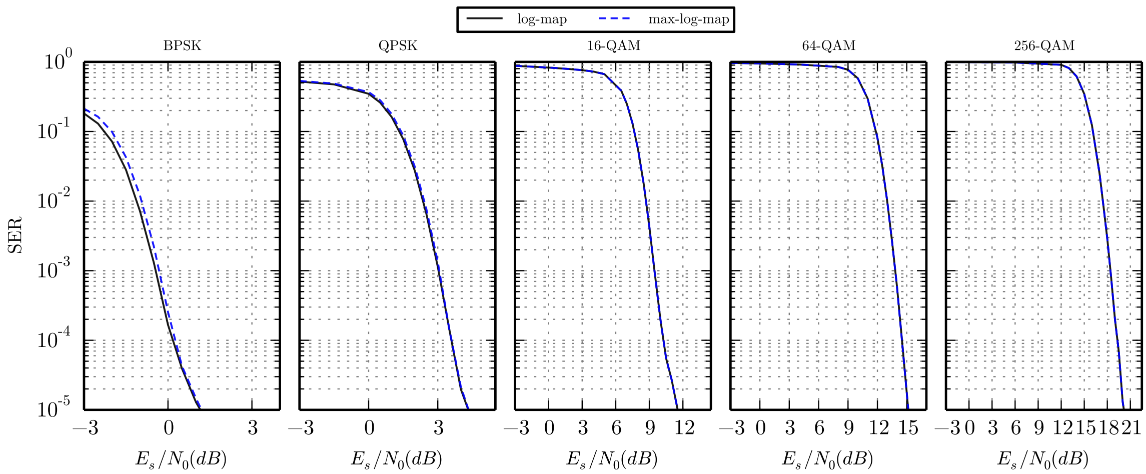



Figure 5.32: Decoding Algorithm Comparison

There are small difference between the log-M$a$P and Max-Log-M$a$P variants mainly in the BPSK and QPSK for small values of $E_s/N_0$. These differences are due to the max formulation presented in Eq. F.7 in Appendix F that is used in each algorithm. The differences between the decoding algorithms become even smaller for higher modulation schemes since higher values of $E_s/N_0$ need to be considered. The BCJR is not represented since the results are, as expected, the same of the log-M$a$P. In terms of performance the Max-Log-M$a$P is the fastest decoding algorithm, with up to 30% gain in execution time when compared with the Log-M$a$P.

The impact of the number of iterations used in each turbo decoder was also evaluated. Fig 5.33 shows the different SERs for the considered modulation schemes when a PB of 16 octets is used along with '1/2' code rate and the Max-Log-M$a$P decoding algorithm. For each value $10^5$ simulations were carried out.

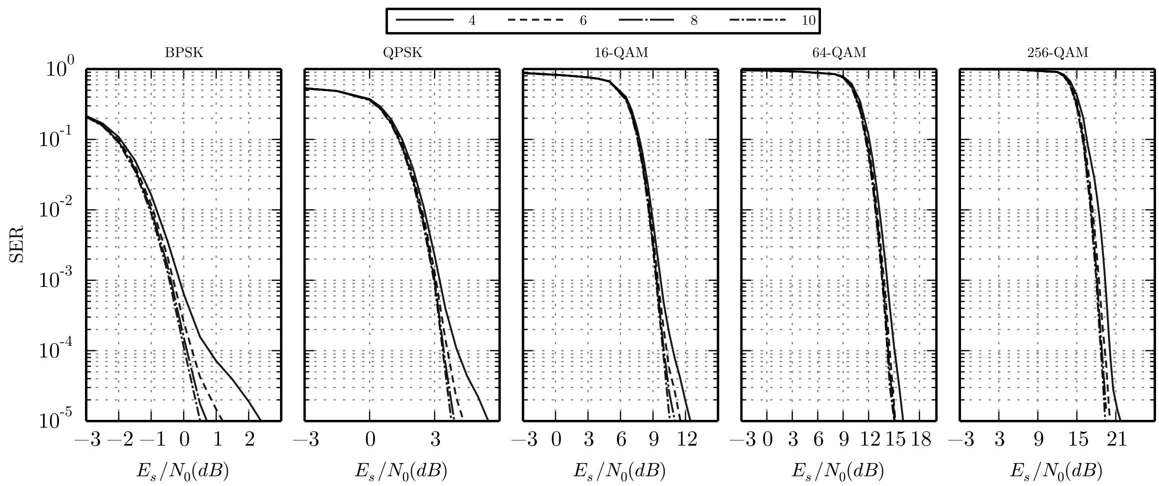



Figure 5.33: Impact of Number of Turbo Iterations

Results show that the IEEE 1901 turbo decoding stabilizes for a relatively small number of iterations. After a determined number of iterations the improvements over the SER curves are very small and usually a trade-off can be established between the achievable improvements and the speed of the decoder, to decide on the number of turbo iterations. In this case a higher number of iterations yields better results due to the implementation of circular estimation of $\alpha$ and $\beta$, as mentioned in the previous Chapter and illustrated in Fig. 4.14, instead of an initial circular state estimation procedure. A visible consequence is the error flooring that is reduced with the increase on the number of iterations.

A comparison between different code rates can also be established for the turbo encoding/decoding system allowing different levels of resilience to errors and consequently having a different impact on the effective bandwidth available to convey information in each subcarrier. Fig 5.34 shows the SER results of the different code rates defined in the IEEE 1901 standard considering a PB of 136 octets. This represents the smallest PB size defined by the standard where all different code rates can be used, as established in Table 13-16 in [67]. The Max-Log-M$a$P decoding algorithm was used with 6 turbo iterations with an approximate soft bit calculation. For each $E_s/N_0$ value $10^5$ simulations were carried out.

As expected, in general, as the coding rate decreases so does the error correction capability, which translates in higher $E_s/N_0$ values necessary for the same level of SER. As the error ratio decreases the

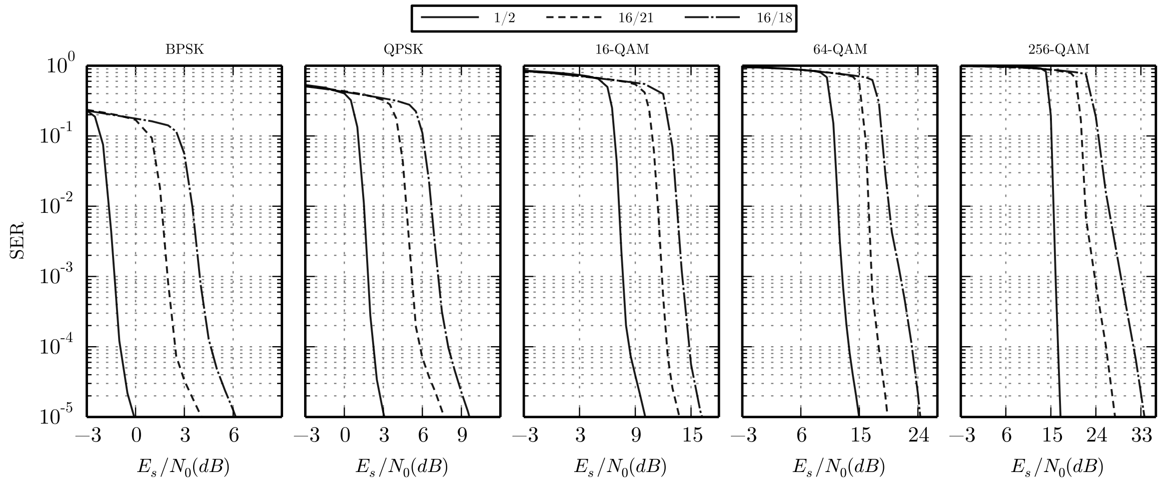



Figure 5.34: Impact of Different Code Rates

SER curves start to get closer to the uncoded cases presented in Fig. 5.29. Another visible aspect is the degradation of the SER for small $E_s/N_0$ values which is a known fact, especially when a comparison between the encoded and non-encoded sequences is established. Similarly in Fig. 5.29 it is visible that higher code rates yield worse SER for low $E_s/N_0$.

The different SER of received sequences considering the available PB sizes defined in the standard are depicted in Fig. 5.35. This intends to illustrate the system ability to deal with the PB-sizes established in the standard. The differences in the achieved results can be attributed to the size of PBs which means that for larger values more bits will be evaluated and larger interleaving patterns will be used.

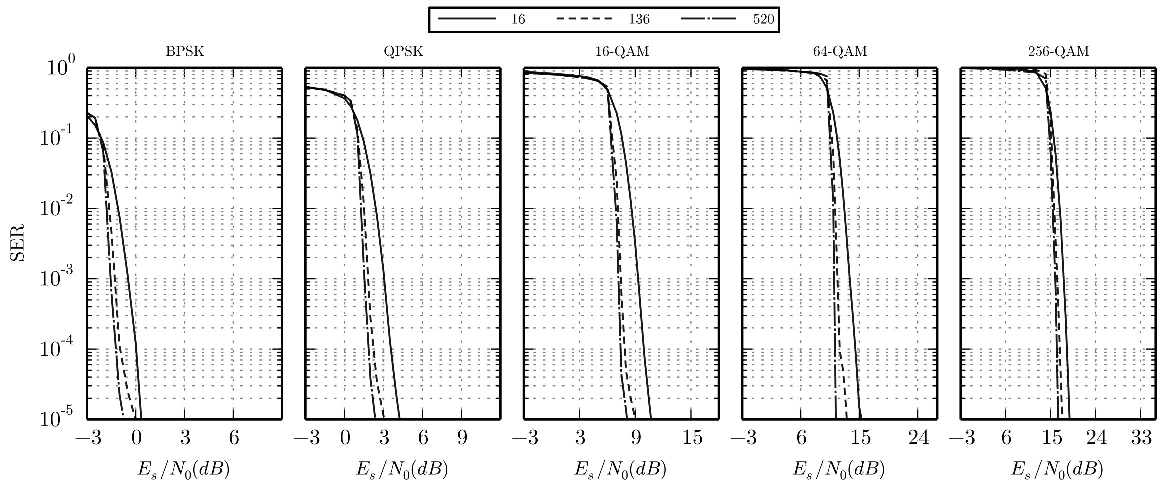



Figure 5.35: Comparison of Different PB Sizes

## 5.6 Communications Uncertainty in Microgrids Laboratory

In order to understand the impact of communications in a near-real environment a series of tests were conducted in a laboratory infrastructure, with a near-real LV electric network configured to adopt the hierarchical control structure of a microgrid. As referred to in the previous chapter, sequences of events were defined to illustrate different operating conditions of a distribution feeder controlled by an MGCC. This required a synchronized approach, to allow an accurate basis for comparison when the uncertainty of communications is evaluated, namely in terms of delays and losses that were considered throughout this section when conducting different tests. It should be noted that despite the effort in ensuring, as much as possible, the same conditions for all the tests presented in this section, the fact is that the interconnection with the upstream distribution network did inevitably introduce variations, namely in voltage and frequency levels. Furthermore, the response time of each controlled device, particularly inverters, can vary due to local control processing mechanism that, among others, involve integrity check and internal configuration procedures that are unavoidable and time varying. Nevertheless, a particular effort was made to bound this delay to approximately 500 ms to minimize the impact of local control actions. Although this type of concern is not likely to take place in field implementations, it was the only way to avoid distortions in the achieved results without compromising the desired interpretation. Two different electric topologies were used for evaluating the system operating in interconnected and isolated operation. In the interconnected case a voltage control event sequence was implemented, whereas in the isolated case a black start procedure was carried out. In both cases the presence of data delays and losses was considered.

### 5.6.1 Interconnected Operation

The evaluation of the communications impact in the interconnected operation was performed with the topology depicted in Fig. 5.36, along with the microgrid hierarchical structure used in this case. Bus A is directly connected upstream to the distribution grid and a cable emulator (LV 100) interconnects it with bus B leading to a voltage drop between them when in operation. In bus B the single-phase inverter prototypes of the Wind Turbine (WT), the Photovoltaic (PV) and the Electric Vehicle (EV) are connected as illustrated in the topology schematic. In this bus a single-phase bank of loads (CL2) is also connected. Bus B is connected downstream to bus C through a cable emulator (LV 50) creating another voltage variation between buses. In bus C a three-phase 4-Quadrant (4Q) back-to-back inverter and a three-phase bank of loads (CL1) are connected. The inverter prototypes are 3 kW, being the EV able to inject power into the bus. The 4-quadrant inverter is a 20 kW device, and as the name suggests, capable of generating or absorbing power according to its configuration. All single-phase devices are connected in the same phase.

A metering infrastructure based on a ModBus/TCP architecture, shared with the SCADA system, was used to monitor each of the devices involved in the tests. Due to the master-slave nature of this system an effort was made to reduce the time between metering requests for each device. This allowed a serialized metering scheme to be implemented with a maximum delay of 15 ms. The system has a configurable sample time, $T_s$, which for the purpose of the tests carried out in the interconnected case was set to 500 ms.

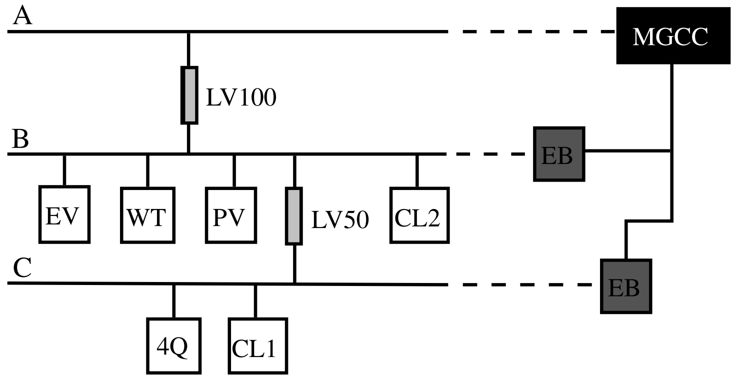



Figure 5.36: Laboratory Electric Topology for Interconnected Operation

A test sequence was defined to illustrate an operating scenario of a microgrid where it is possible to see the participation of the different elements under the hierarchical control structure. The sequence is made up of the following events, which are also identified in Fig. 5.37:

(a) At $t = 10$ s the 4Q inverter is initialized as a three-phase microturbine outputting 6.5 kW, which intends to cause a voltage increase in the microgrid;

(b) At $t = 25$ s the PV inverter is started with a 2.8 kW power output, further increasing the voltage imbalance;

(c) At $t = 56$ s the voltage droop control of the solar inverter is activated and an immediate response is expected due to the local control action;

(d) At $t = 81$ s the WT inverter is started also with 2.8 kW that introduces a voltage increase that is attenuated by the local control of the solar inverter;

(e) At $t = 106$ s the voltage droop control of PV inverter is started and cooperatively with the solar inverter droop control ensures that the voltage level is reduced accordingly;

(f) At $t = 131$ s the voltage control of the 4Q inverter is activated, with immediate impact on the voltage level which is lowered in the bus C and consequently in bus B where the remaining inverters are connected, allowing them to increase their power output;

(g) At $t = 171$ s the EV starts charging, allowing neighboring solar and wind inverters to increase their power output while the voltage values are kept stabilized;

(h) At $t = 186$ s the voltage droop control of the EV charger is activated, which allows the EV to increase its power consumption, since the solar and wind inverters are able to increase their power production due to the previous activation of their own voltage droop control;

(i) At $t = 206$ s the first load step of approximately 3.6 kW of CL2 is activated, to emulate a load increase, which leads the EV inverter to marginally reduce the charging rate, mainly because the 4Q reacts by increasing the power output along with the PV and WT prototypes that have their droop control, allowing to limit the curtailment in the EV charging process;

(j) At $t = 221$ s the second load step of CL2 is also activated totaling 10 kW three-phase, making the EV charging rate to reduce further and the 4Q, PV and WT inverters to increase even more their power output;

(k) At $t = 261$ s the available generation units are all disconnected, creating a generation imbalance and consequent voltage drop;

(l) At $t = 286$ s the third load step of CL2 is also activated totaling 18 kW, which aggravates the voltage drop that in turn makes the EV charger to react and start injecting power to compensate the voltage drop, creating a load peak case where there is no microgeneration available other than the EV;

(m) At $t = 306$ s the first single-phase step of CL1 is activated totaling 1.0 kW, making the EV charger to increase its power output, which causes the associated bus B to have a higher voltage level then the upstream bus A;

(n) At $t = 316$ s the second single-phase step of CL1 is activated totaling 2.8 kW, lowering the voltage in bus C and thus requiring even more power to be injected by the EV inverter;

(o) At $t = 360$ s, all loads are disconnected along with the EV inverter. The sequence finishes and the voltage levels in all buses are again similar to the initial state.

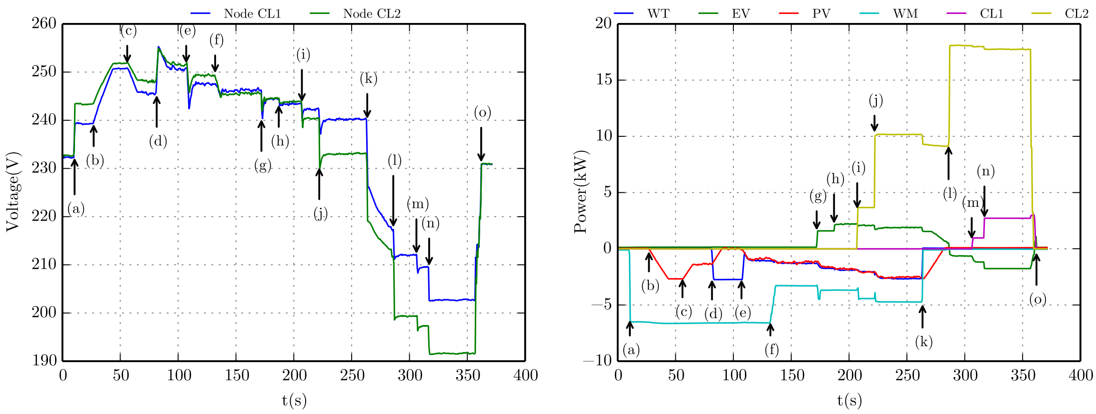



Figure 5.37: Interconnected Microgrid Response

Events (c), (e), (f) and (h) result from control action where set-point are exchanged and therefore are subjected to the uncertainties of communications. All other events are part considered to be part of the defined sequence operation.

Negative power values represent the injection of power into the microgrid, typically by the prototypes or the 4-Q inverter, whereas positive value represent the consumption of power, typically by loads or by the EV inverter when charging the batteries.

In order to understand and evaluate the impact of communications in the microgrid operation a set of tests was conducted using the same event sequence that was described. A variable delay was introduced in the data link between the MGCC and the EB by means of controlling the communications interface at the receiving end, emulating in this way the associated uncertainty. For this purpose, two communications interfaces were used at the receiving end: one without delays is used to forward set-points that intend to connect or disconnect devices, which are synchronized events with the purpose of ensuring that similar test sequences are produced; and another with delays through which control actions from upper entities, in this case the MGCC, are forwarded to the respective local controllers.

A delay was configured in each EB node, as the receiving end, based on a random number generator implemented by the OS kernel over the controllable communications interface. This allowed the implementation of a probabilistic delay behavior, which was associated with a predefined jitter. To illustrate the impact delays it was decided to show the variations that occurred in the response to each of the inverter prototypes that participate in the control actions associated with the test sequence, namely the remote parameter configuration of voltage droop control. Delays of 2 s and 4 s were considered along with a jitter of 200 ms and the impact on the response of each configurable inverter was captured by the metering infrastructure.

Fig. 5.38 illustrates the impact of delays in the PV inverter response.

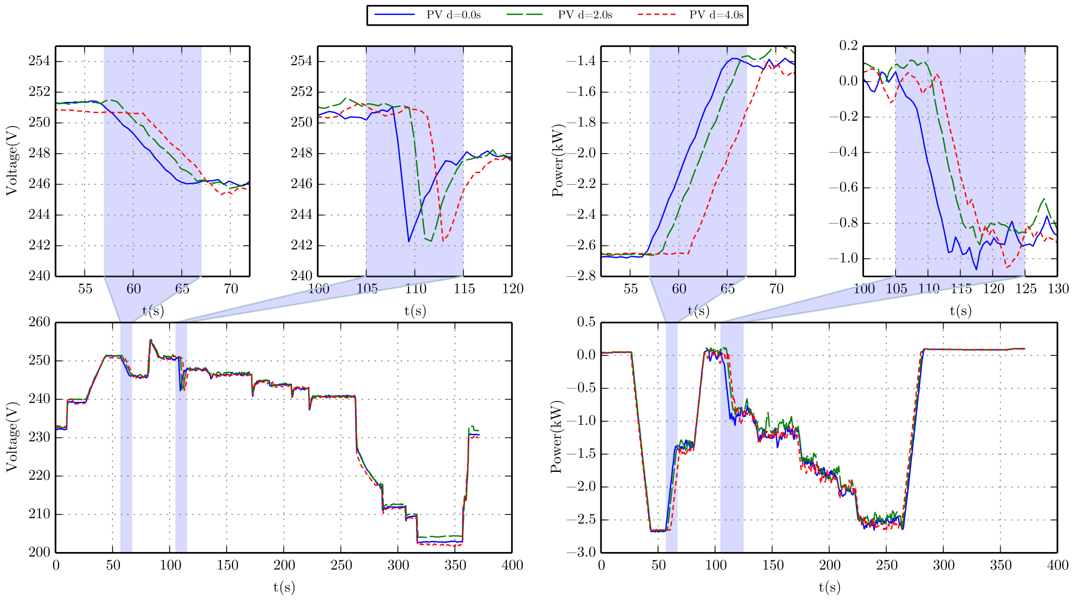



Figure 5.38: PV Inverter Response with Delays

As earlier described the PV inverter is started at $t = 25$ s, visible in the bottom right graph, and the voltage droop is activated at $t = 56$ s and it is highlighted in the zoomed representation of the inverter power output between $t = 55$ s and $t = 70$ s. As already referred, this variation is due to local control action governed by the configured droop characteristic. The introduced delay shifts the inverter power output response which is visible in the nearly parallel power injection decrease. Conversely, the voltage reduction suffers a similar effect.

There is however a similar voltage decrease phenomenon between $t = 80$ and $t = 100$ s, which is due to similar actions performed in the WT inverter, which are visible at the terminals of the PV inverter. Since the delay variation is nearly the same, the shifted response is also similar, as it will be shown in the WT inverter case.

In the WT inverter a similar shifted output power is visible in the bottom graphs and highlighted in the upper zoomed versions in Fig. 5.39. The previously described PV droop action is visible at the WT inverter terminals in the form of voltage variation. On one hand there is no response from the PV inverter since it is only connected at $t = 66$ s, hence no power variation is visible. On the other hand after being connected and the voltage droop control configured and activated, the response of the WT inverter and the impact of communications delays are visible.

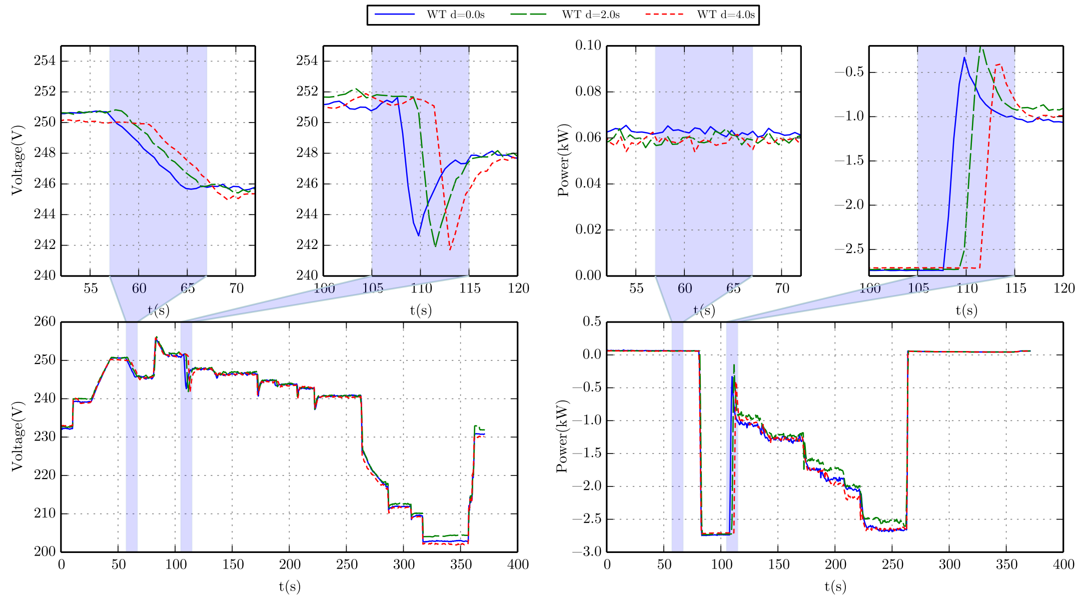



Figure 5.39: WT Inverter Response with Delays

The response of the EV inverter/charger depicted Fig. 5.40 exhibits a similar characteristic to the WT inverter between $t = 40$ s and $t = 60$ s interval for the same reason.

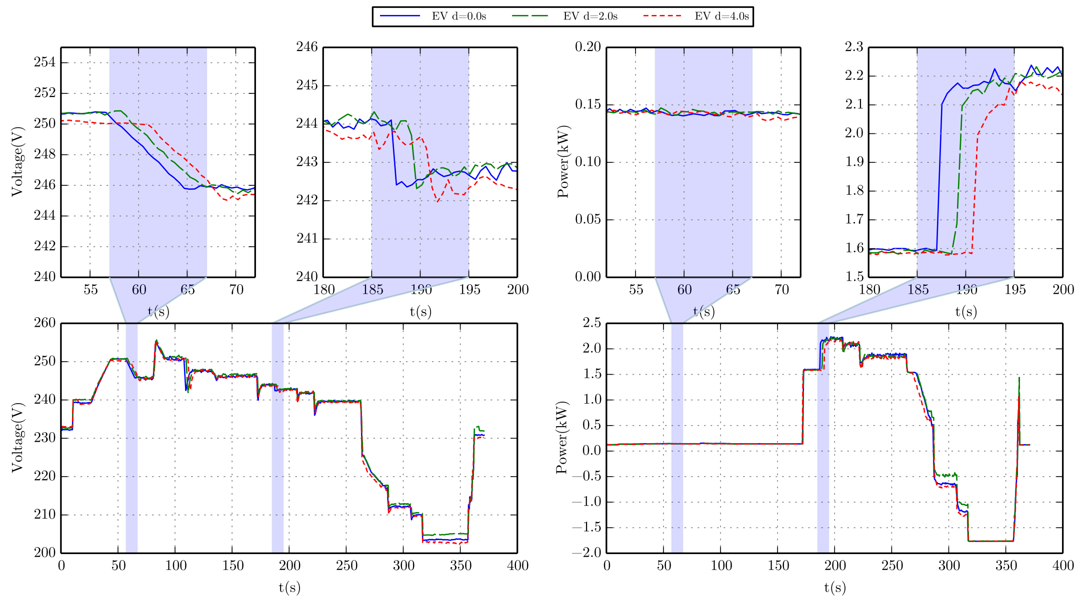



Figure 5.40: EV Inverter/Charger Response with Delays

The EV inverter response is visible between $t = 185$ s and $t = 195$ s where the droop parameterization values are received and the droop control allows the charging rate to increase thanks to the combined action of the PV and WT inverter in increasing their power production. Their power increase is visible in both Figs. 5.38 and 5.39 power output from $t$ = 185 s onward. The reduction of the voltage level at $t$ = 242 s is immediately compensate by the EV inverter whose droop control allows the EV to reduce its charging power. Furthermore, since in the previous EV droop set-point exchange the V2G mode was also activated, the load increase with the activation of the three load banks of CL2 at $t$ = 286 s, led the EV inverter to automatically start injecting power into the grid to compensate for the associated voltage drop.

A similar approach was taken to explore the impact of information loss; for this purpose the receiving node interface responsible for forwarding control data was configured with different loss ratios. However, given the limited size of the laboratory microgrid and consequently the number of set-points to be exchanged in the previously mentioned sequence, only one scenario with losses was considered. A high loss ratio of 40% was considered to ensure that set-point failures occurred without having to extensively repeat the sequence in order to observe the impact of information loss. The impact of losses was evaluated together with an incurring average delay of 2s, as an unfavorable scenario, which combines the uncertainty of both delays and losses.

Fig. 5.41 depicts once again the PV inverter response.

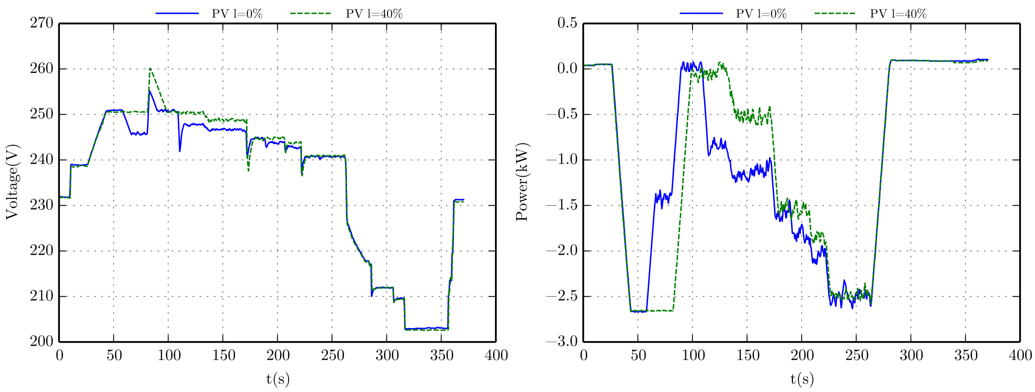



Figure 5.41: PV Inverter Response with Losses

When losses are considered ($l$ =40%) the voltage droop activation fails to be delivered to the PV inverter, thus the flat response from $t$ = 55 s to $t$ = 85 s both in terms of voltage and active power. The PV inverter voltage droop is activated at $t$ = 80 s due to a new set-point exchange that is now successfully received by the prototype. This delayed response originates a visible increase in the voltage level with the consequent power increase. The difference in the response after $t$ = 105 s is explained by a loss in the WT inverter as will be shown afterwards.

The WT prototype response is illustrated in Fig. 5.42 and like in the PV case there are visible differences when losses are considered. The only loss occurs at $t$ = 105 s where the activation of the voltage droop fails allowing the inverter to keep injecting power at the rated level. This makes the voltage level to rise above the other cases. At $t$ = 170 s set-points are issued and the PV inverter voltage droop control is activated with success, making the prototype to react accordingly and similarly to the other cases. As it was referred previously, the set-point loss prevented the PV prototype from injecting power since the WT droop control was not activated. In Fig. 5.41 it is possible to observe that the PV inverter injects less power between $t = 105$ s and $t = 170$ s.

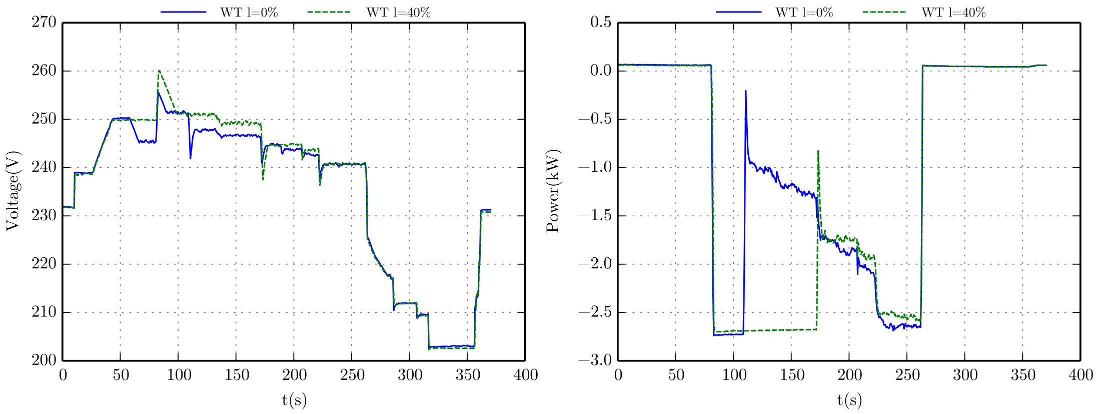



Figure 5.42: WT Inverter Response with Losses

The response of the EV inverter presented in Fig. 5.43 shows the impact of losses too.

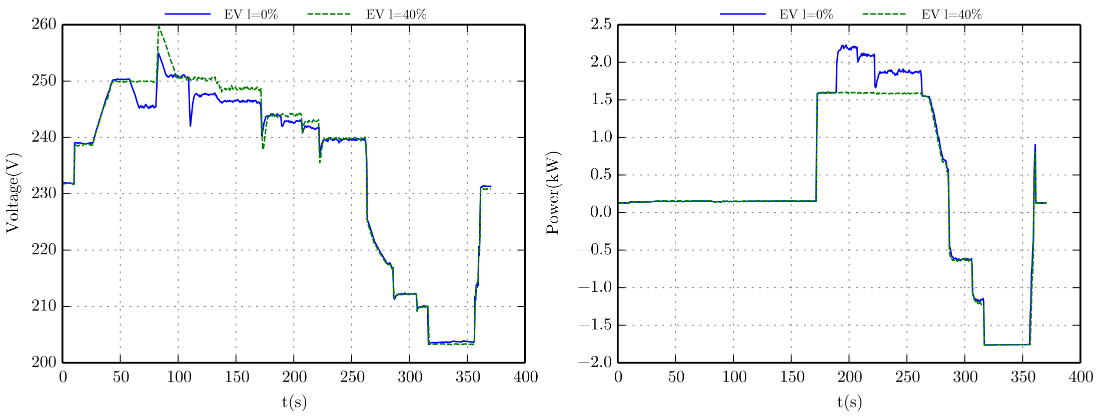



Figure 5.43: EV Inverter Response with Losses

In this case, due to the loss of the EV droop control activation, the inverter is unable to take advantage of favorable conditions in terms of voltage level to increase its charging rate. As such it is only capable of drawing the initially set 1.5 kW at $t = 171$ s. Due to the round of set-points exchanged at $t = 261$ s the remaining inverters are disabled and the EV receives the droop activation successfully allowing it to resume the expected control pattern and injecting power into the grid, to compensate the voltage drop due to the load increase.

The 4Q inverter is not affected by any set-point loss, which is visible on the response presented in Fig. 5.44. Nevertheless, the local control response is affected by the set-point loss occurred in the WT droop control activation. Since the WT is not able to reduce the injected power in response to the voltage increase, the 4Q has to reduce further the injected power, when compared to the case where no losses occur. When the WT droop control set-point is finally activated at $t = 170$ s the 4Q is then able to increase the power production to compensate the voltage drop.

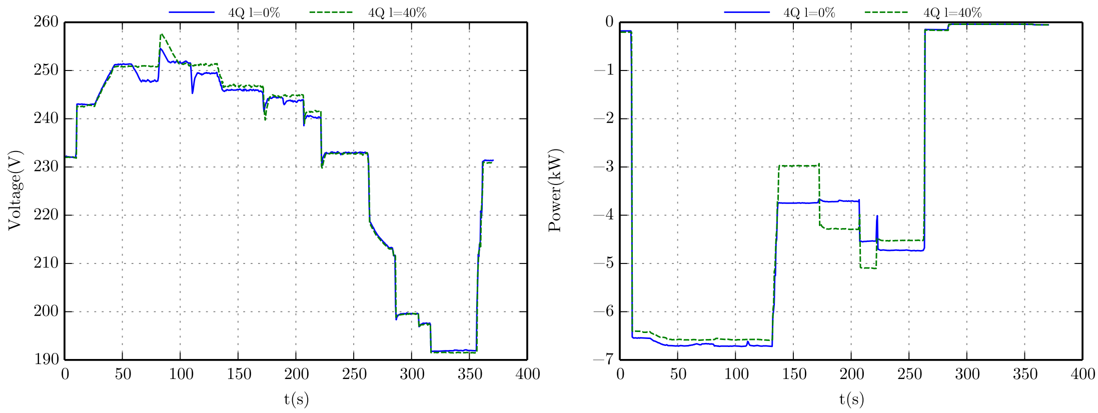



Figure 5.44: 4Q Inverter Response with Losses

The overall results for the microgrid interconnected operation showed that the impact of delays resulted mainly in the delayed response of each of the target units that had their set-point exchange delayed. As for losses the main impact was the absence of participation of the affected targets, like the EV, which were not able to take advantage of the network conditions to enhance their participation.

### 5.6.2 Isolated Operation

The evaluation of the impact of communications uncertainty was conducted in an isolated microgrid configuration, over which a black start procedure was implemented. The electric network configuration that was used in this case is represented in Fig. 5.45, along with the microgrid hierarchical structure. Like in the previous electric configuration all single-phase devices are connected to the same phase

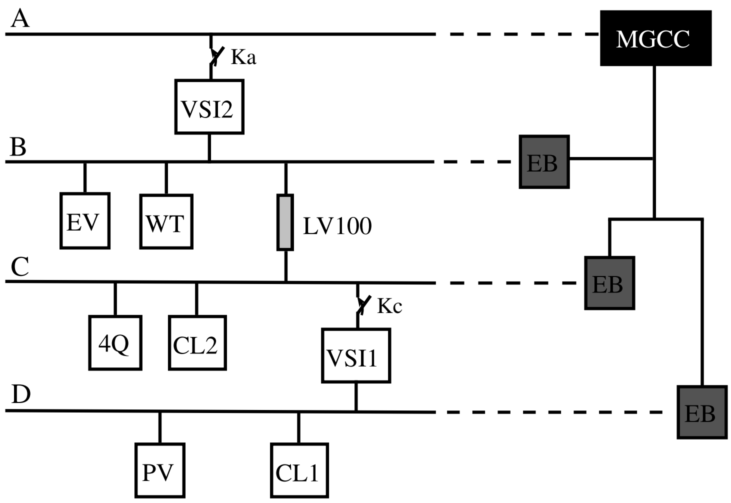



Figure 5.45: Laboratory Electric Topology for the Black Start Procedure

A specific sequence was established for the laboratory MG black start procedure according to the previous general guidelines, to enable the participation of the available elements under the hierarchical

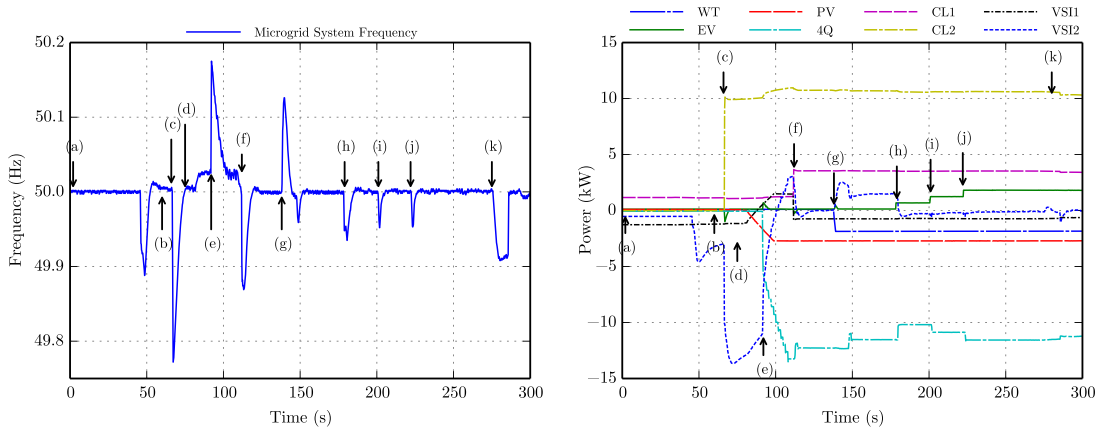



Figure 5.46: Isolated Microgrid Global Response

control structure. For each test it is assumed that the MG is already isolated with the opening of contactors Ka and Kc. An initial load is connected to the isolated system to allow the VSIs to detect its presence and set the system frequency accordingly. The black start sequence is then initialized and is made up of the following events illustrated in Fig. 5.46:

(a) At $t = 0$ s the Kc contactor is closed interconnecting the VSI1 with the isolated microgrid allowing the synchronization between VSIs to occur;

(b) At $t = 60$ s the P-f droop control of the EV inverter is activated, with no immediate visible effect;

(c) At $t = 65$ s the first two load steps of CL2 are connected totaling 10 kW;

(d) At $t = 80$ s the PV inverter is started injecting 2.8 kW, which introduces a frequency increase that is attenuated by the EV P-f droop control;

(e) At $t = 90$ s the 4Q inverter is started at 6.0 kW with the activation of the secondary control, which is responsible for the subsequent increase in power injection;

(f) At $t = 110$ s the first two load steps of CL1 are connected totaling 3.8 kW;

(g) At $t = 135$ s the WT inverter is started at 2.0 kW and the 4Q inverter secondary control is again activated, to adjust its support to microgrid;

(h-j) At respectively $t = 170$ s, $t = 200$ s and $t = 220$ s the EV starts charging in steps, totaling 0.6, 1.2 and 1.8 kW and the 4Q secondary control is triggered by the MGCC to support the EV charging procedure each time the charging power is increased;

(k) At $t = 295$ s the sequence finishes with the reconnection of the isolated microgrid with the upstream network by closing the Ka contactor.

Events (b) to (j) result from control action where set-point are exchanged and therefore are subjected to the uncertainties of communications. All other events are considered to be part of the defined sequence operation and are not subjected to variations other than those associated with the event itself.

Like in the interconnected operation case, delays were introduced in the data exchange of the black start procedure, using the target EB node emulation module. Delay variations of $d = 2.0$ s and $d = 4.0$ s were considered when comparing with the base scenario were no delays are considered, thus making it the ideal case. The different frequency responses of the isolated microgrid are due to the presence of delays is portrayed in Fig. 5.47.

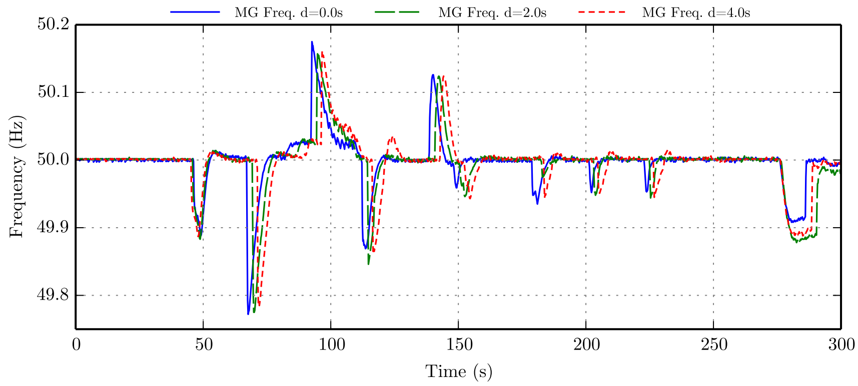



Figure 5.47: Impact of Delays in the MG Frequency in the Black Start Procedure

Generically, the main impact of delays in the frequency is mostly a delayed response in the black start procedure. The initial frequency variation is due to the synchronization of the VSI1 with the isolated microgrid, and it depends on the internal synchronization procedure triggered by the VSI which independently establishes the exact time instant to be interconnected with the VSI2. Similarly, the final frequency variation is due to the microgrid reconnection with the upstream network, which is also dependent on the VSI2 internal synchronization procedure. As such, discrepancies are observed in both cases despite the fact that they are not related with the presence or not of delays in the black start procedure.

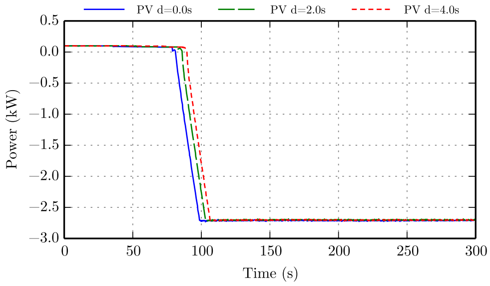
In the black start procedure all the information exchanged within the microgrid is issued from the MGCC, which is the node responsible for supervising the implementation of the associated actions. This means that in the above discriminated black start procedure all information exchange is subjected to the potential uncertainties introduced by the communications infrastructure, since all control actions are issued from the MGCC.

In Figs. 5.48 and 5.49 the contribution of all participating entities in the back start procedure is represented. As suggested by the frequency response presented before, the impact of delays is mainly associated with a shifted response of the different participants.

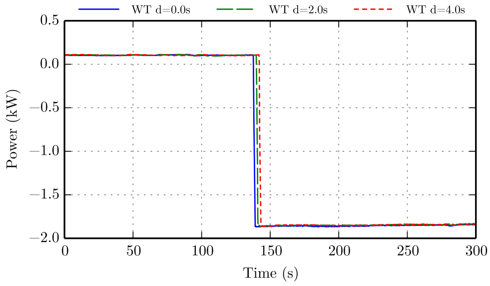
In the particular case of the EV frequency response it is visible that different frequency excursion magnitudes may occur, mainly due to the time instant upon which the local control is set to react.

The most significant response variation is visible in the 4Q inverter that by delaying its response to the instant upon which the MGCC required its action to take place ends up observing the system at different operating conditions. Since the VSIs are actively supporting the isolated system, by delaying the action of the 4Q inverter, they are allowed to change their power according to the system frequency sooner, and hence inhibit or reduce the participation of the 4Q inverter as a supporting unit.

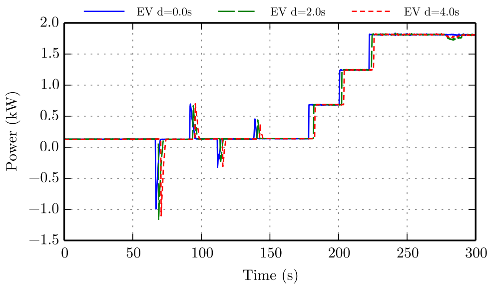
A similar strategy was followed to evaluate the impact of losses using the same black start procedure described earlier. Data losses were thus introduced in the different communications links and a comparison with the ideal case, where no losses occur, was established. Unlike delays, losses can have a significant



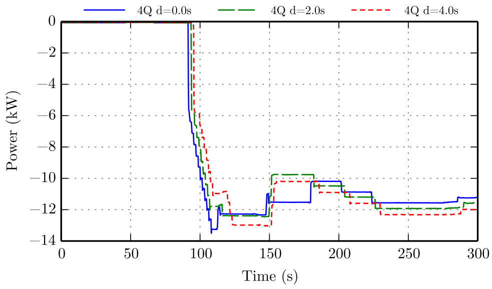

(a) PV Inverter




(b) WT Inverter

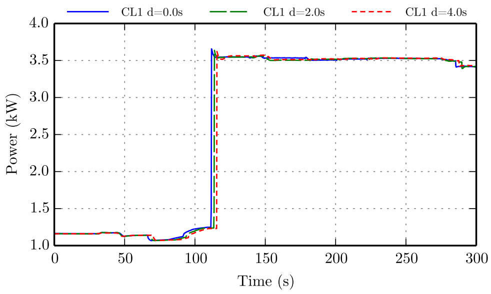



(c) EV Inverter

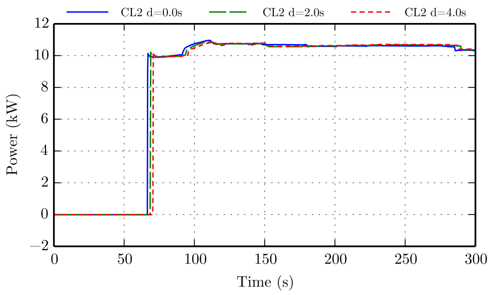



(d) 4Q Inverter

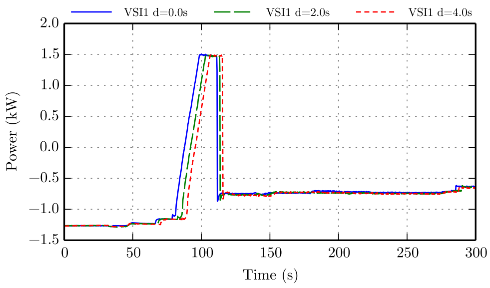
Figure 5.48: Presence of Delays in the Black Start - Part 1



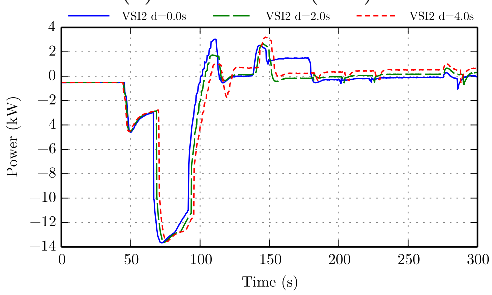

(a) Load Bank 1 (CL1)




(b) Load Bank 2 (CL2)




(c) Voltage Source Inverter 1 (VSI1)




(d) Voltage Source Inverter 2 (VSI2)

Figure 5.49: Presence of Delays in the Black Start - Part 2

impact in the system frequency response, since the participation of some entities is compromised. The configured loss ratios affect indiscriminately generators and loads and, as such, the impact can be different even when considering the same loss ratio.

The objective was the illustration of the impact of information loss in black start procedure. Given that extensive testing under laboratory conditions is both time consuming and contributes to the premature wear of the related equipment and materials, generic loss ratio values were considered as typical examples. As such of l=15%, l=30% and l=45% values of loss ratio were established. Despite the fact that some of these are unrealistic values, they were used to implement a severe loss of information and evaluate its impact.

Fig. 5.50 represents the isolated microgrid frequency response when different data loss values are considered in the execution of the black start sequence. There are visible differences in the frequency response as consequence of the information loss phenomenon, which according to the affected target can have different impacts. Like in the previous case, where delays were considered, the initial and final variations depend on the internal synchronization scheme of the VSIs.

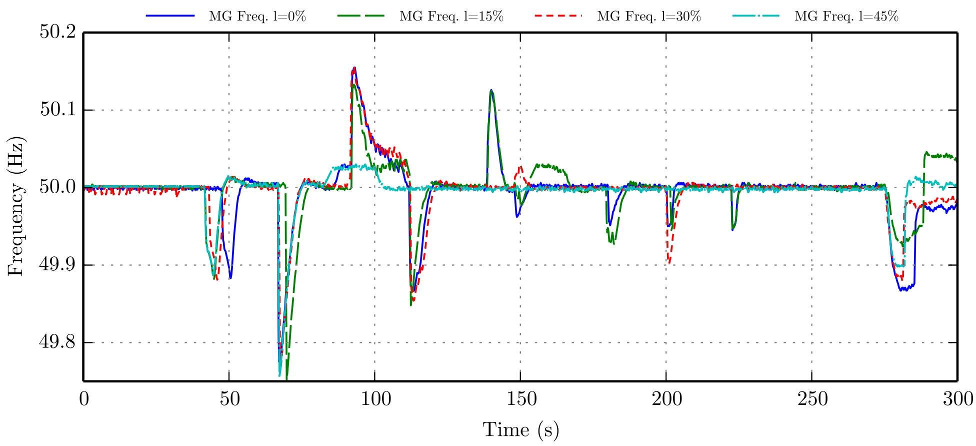
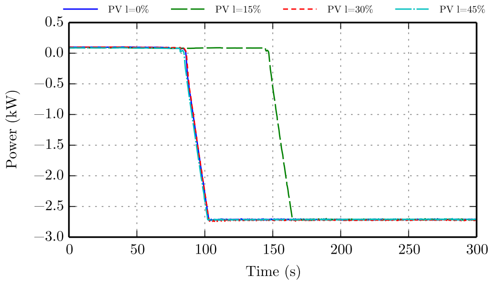



Figure 5.50: Impact of Losses in the MG Frequency in the Black Start Procedure

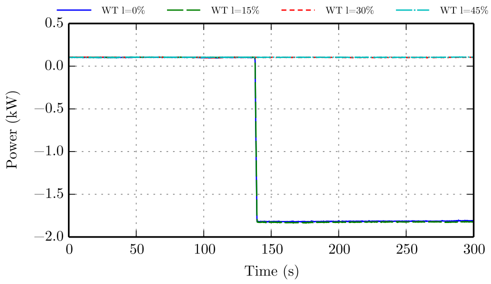
In Figs. 5.51 and 5.52 the response of the different participating elements of the black start procedure when information losses are considered is portrayed.

In the case where the loss ratio is set to 15%, only the PV inverter set-point is lost, which originates a generation imbalance that is compensated by the immediate action of the VSI1 and by the secondary control of the 4Q inverter. On one hand the VSI cannot take advantage of that resource to charge its batteries temporarily as it so happens in the remaining cases. On the other hand the 4Q is forced to injected more power. In this case a new set-point is re-issued to the PV inverter at the same time the WT inverter is called upon participating. Since a successful data exchange takes place the PV primary resource becomes available and the VSI1 is able then to reduce its participation and a convergence to -1.3 kW occurs, which makes the 4Q inverter able to reduce its participation.

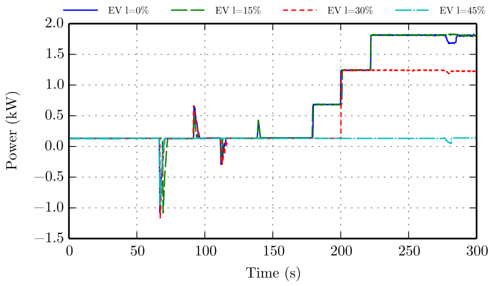
For the case of a loss ratio of 30% the activation of the WT inverter fails and the 4Q inverter is called upon compensating for this generation imbalance by injecting the necessary amount of power. In this case the first and last charging set-points sent to the EV inverter are also lost, which results in the EV charging at 40% until the end of the restoration procedure. The absence of WT generation, the presence of the EV as a load, and a failed set-point to the 4Q inverter forces the VSI2 to inject more power instead, to compensate for the power imbalance.



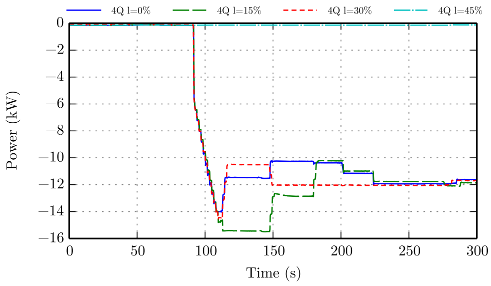

(a) PV Inverter




(b) WT Inverter

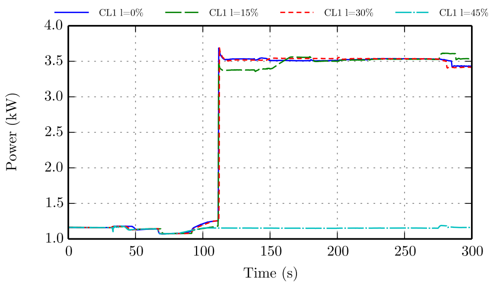



(c) EV Inverter

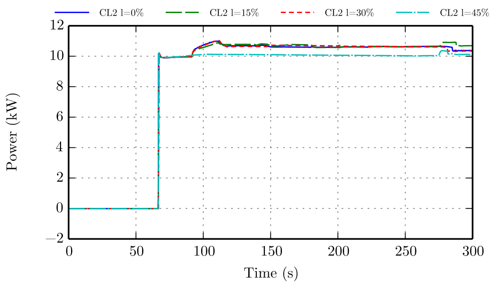



(d) 4Q Inverter

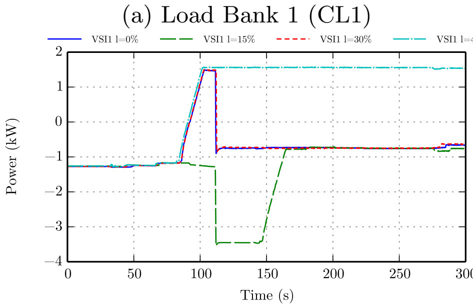
Figure 5.51: Presence of Losses in the Black Start Procedure - Part 1



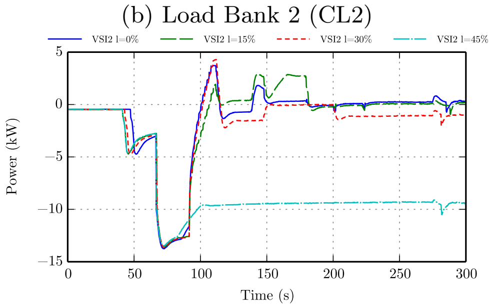

(a) Load Bank 1 (CL1)




(b) Load Bank 2 (CL2)




(c) Voltage Source Inverter 1 (VSI1)




(d) Voltage Source Inverter 2 (VSI2)

Figure 5.52: Presence of Losses in the Black Start Procedure - Part 2

In the last case, where a 45% loss ratio is considered, there is a failure in the activation of the second step of the load bank 1 (CL1) that creates an imbalance with an excess of generation that is used by the VSI1 to charge its batteries, a situation that is maintained until the sequence is completed. With this situation the frequency deviation is not enough to promote the participation of the EV inverter, which is visible both in Fig. 5.50 and 5.51c. There is also a failure in the activation of the 4Q inverter and as a result the VSI2 is requested to participate until the sequence is finished. In this extreme case all the EV charging set-points fail and as such there are no changes in the microgrid frequency after $t = 100$ s, except the one related with the reconnection of the isolated system at the end of the black start.

The overall results for the isolated operation showed that the impact of delays resulted mainly in the delayed response of the affected set-point targets, like in the interconnected case presented earlier. However the impact of losses is in this case are higher with visible effect on the microgrid frequency response. The main consequence is the unbalanced participation of some units to compensate for a set-point loss as it is shown in the presented figures with the discriminated unit participation. The consequences are not more severe in this case due to the capacity of VSIs to sustain the MG as significant supporting units.

## 5.7 Summary and Main Conclusions

This chapter presented the main results of the work conducted in this thesis. A control algorithm was developed to allow the assessment of the uncertainties of communications systems in hierarchical multi-microgrid systems. For this purpose a dynamic tool that interacts with Eurostag was created; it allows the fast simulation of different cases using an AGC based control scheme associated with a MILP formulation to derive the necessary set-points to be exchanged. Results showed that when operating in emergency conditions the defined secondary control strategy was able to recover the system frequency in a small time frame. Smaller sample periods were shown to marginally improve the system response at the expenses of assigning more set-points. The introduction of variable delays to the set-point exchange mechanism allowed a non-synchronized implementation of the control actions with negligible impact on the overall system response if the delays were kept below the sampling period. Otherwise the system response could vary significantly with outdated set-points being implemented at the same time newer ones were calculated and dispatched. This created counterproductive control actions from the centralized secondary control. This impact was not more severe because in the test network that was used the presence of primary controlled devices, namely MV and LV VSIs, were able to support the transitory intervals between the decisions from the secondary control. A Monte Carlo simulation was conducted to assess the impact of different loss ratios. It was shown that significant variation could be observed for higher loss ratios and for cases where set-points targeted at relevant participating entities were affected by losses.

The characterization of Portuguese distribution feeders allowed a better understanding of the geographic context where communications systems will have to be deployed to support monitoring and control applications. Results showed the viability of having randomly generated scenarios were the node positioning could be established with specific probability distributions, which were evaluated against real data provided by the Portuguese DSO. This evaluation allowed the perception of the potential number of nodes and involved distances according to the different types of scenarios that were established.

The WiFIX wireless mesh solution was evaluated using the generation of scenarios with different node positioning according to the type of distribution network. A simple and fast positioning algorithm was used to deploy the necessary number of relay nodes to ensure the proper connectivity between the GW and all the communicating nodes (MAPs). Results showed that on average a small number of relay nodes was necessary to guarantee the full network coverage, despite the diversity of scenarios associated with the M-C method. Modifications to the original WiFIX were necessary to handle the specificities of these type of wireless mesh networks in the context of the Portuguese distribution grids. Results also showed that on average small RTTs are achieved in a complete a polling round. Those values are compatible with the delay values introduced in the MMG control system. Even if two polling rounds are considered, one for collecting state information and another for dispatching control set-points, the overall delay is still within reasonable values. Furthermore, given that in a round of control actions typically only a fraction of the available controllable portfolio will be requested at each time to participate, the RTT values can be even lower. The polling scheme allows this dynamic selection of targets at no cost since the scheduling is imposed by the master node. It also gave all communicating nodes the opportunity to exchange information with the GW, which is expected to act as a hierarchical controller node. Overall it was possible to show that a wireless mesh network based on WiFIX is capable of supporting the control application and in all cases guarantee a complete coverage of the network in both LV and MV distribution networks.

The implementation of a simplified IEEE 1901 PHY layer allowed the evaluation of the effect that non-ideal characteristics of this type of system have on the implementation of real systems where hardware constraints have a significant impact. The implemented system allows the use of different $E_s/N_0$ values, which can be collected from on-the-field tests, and help in the calibration of a propagation model that account for non-ideal phenomena like error flooring. It was possible to show that despite the fact that BB-PLC can be pointed out as a potential solution for the last-mile segment, the propagation conditions of the communications channel will likely require higher code rates and the use of modulations schemes with smaller constellations to ensure a high level of resilience. One of the issues associated with the BPL implementations is the allowable transmission frequencies and, as such, the number of allowable subcarriers to convey data, which are determined by regulating entities in each country.

The laboratory implementation of a microgrid system and communications infrastructure allowed the evaluation of the impact of the uncertainties of communications in a near-real scenario. With variable delays and data loss ratios, results showed that the impact of communications can have different consequences, depending on the microgrid operating state. For the interconnected mode no major impacts were visible whereas in the isolated mode the delays contributed to the delayed response of the system and data losses had a greater impact, which required in some cases an extra contribution from the remaining controllable units to ensure the necessary system stability.

# Chapter 6

# Conclusions

The paradigm change that is taking place in the electric power industry, found in concepts like the smart grid, has motivated a significant amount of research effort in accommodating new domains and players. Advanced control strategies have been defined to take advantage of the dissemination of RES in distribution grids, which along with controllable loads and electric vehicles promise to deliver an enhanced and unprecedented service exchange philosophy. These services will rely on different applications with varied requirements that can be differentiated not only in terms of context but also in terms of time frame. Last-mile communications systems should ensure the necessary connectivity between participating entities of electric distribution control schemes while meeting different requirements of both technical and market operation domains. It was in this scope that the work presented in this thesis was carried out. Hence, this chapter presents a general discussion of the outcomes and results presented throughout this thesis in the context of last-mile communications for smart grids. The main contributions are highlighted and analyzed; open topics are identified and discussed pointing out the guidelines for future work.

## 6.1 Analysis and Discussion of Contributions

The work presented in this thesis sought to provide relevant contributions towards the integration of communications systems in future electric distribution networks. Consequently, the main contributions can be divided into:

1. **Integrated models and data flows:** The different architectural models presented in the state-of-the-art established the interaction among diverse participants defined within the smart grid concept. These architectures result from interpretations of different realities but also share common aspects that set a basis for future extrapolations despite the differences in context. The models of SGs and associated data flows presented in Chapter 3 allowed a better understanding of the involved entities and foreseeable interaction among them. The two perspectives presented with the logic model account for the integration of the technical and market operations considering different levels of integration and participation of controllable entities. A segregation of the information flows concerning the technical and market operation was proposed. In one hand the information exchange has clearly different scopes and concerns typically different operation time frames. On the

other hand different information flows and different communications requirements can be established with implications on the technological solutions capable of meeting different QoS indices.

2. **A tool for evaluating a hierarchical MMG control in the presence of uncertainties:** a hierarchical control scheme based on a multi-microgrid structure was designed to deal with the operation of a MV network in emergency operation. A configurable tool was designed and implemented to allow the evaluation of the impact of uncertainties associated with the supporting communications infrastructure used to exchange control set-points in a specific electric network. A Monte Carlo simulation tool was implemented to evaluate the performance of the control scheme considering the variability of information delays and data losses of the set-point exchange mechanism and its impact on the system response. Results presented in the previous chapter showed that the presence of controllable entities inside the MMG can accommodate delays and the resultant non-synchronized control actions and allow the system operation despite the loss of set-points.

3. **Characterization of the geographical context of electric distribution networks:** A geographic characterization of Portuguese MV and LV distribution feeders was carried out with the purpose of providing context information regarding the typical placement of potential communicating nodes (ex.: substations, secondary substations and energy boxes) considering different types of scenarios (rural, mixed and urban). A set of GoF tests was carried out and results showed that a set of candidate probability distributions is able to accurately represent the data provided by the Portuguese DSO and thus establish the basis for the random generation of several cases for node positioning for each of the considered scenarios. This allowed the evaluation of a WMN implementation with different node positioning in both LV and MV scenarios.

4. **The feasibility of WMNs in providing a communications infrastructure for SG applications:** a WMN implementation based on WiFIX was designed and evaluated considering the outdoor scenario. The original WiFIX implementation was adapted to cope with the contextual specificities of WMNs when deployed in the different LV and MV distribution networks under evaluation. Results showed that full connectivity between all nodes and the GW was possible in all the considered scenarios. In most typical LV scenarios connectivity with the GW was possible without relays, whereas in MV scenarios relay nodes had to be installed using a fast and simple relay allocation algorithm. Furthermore, it was also possible to show the impact of the average hop count and different node density associated with each type of scenarios in the achievable average RTT and throughput. A complete polling sequence was shown to be successfully completed in less than 1 s in all scenarios. The use of more than one polling sequence to implement a control action round, namely one for state evaluation and another for implementing the necessary control actions, can be balanced with the limited number of target nodes of each control set-point exchange sequence. Nevertheless the involved delays are within the time horizon established for example for the MMG control scenario evaluated previously. Besides, the achieved throughput values are aligned with the majority of the values identified in the analysis of communications requirements.

5. **The evaluation of the IEEE 1901 PHY:** the recognized difficulties in conveying information using a PLC based medium has led to its consideration for carrying data from the inside of a building to its vicinity. In fact, given the difficulties of wireless solutions to ensure connectivity inside

buildings it seemed natural to consider PLC as a strong candidate to convey information from the customer premises to the exterior of a building. The fact that recent BPL implementations are targeting outside the building communications also suggests its applicability in conveying information to the outside of the building. This can be regarded as a solution to convey information to and from the energy boxes or any other control entity installed in each customer and a data concentrator that is able to exchange aggregated information with for example an outdoors WMN from a system operator. Due to the recognized difficulty in establishing propagation models for PLC an alternative was to analyze the PHY layer characteristic of the IEEE 1901 as the current main BPL standard to allow an in-building communications solution. The FEC mechanism established in the standard was evaluated using a set of IEEE 1901 system blocks designed to emulate the communications at PHY level using some simplifications. A turbo decoder system was implemented using a circular metric scheme to allow an efficient and fast iterative decoding strategy. Results showed the validity of the turbo decoder against the theoretical formulation, allowing a comparison between the theoretic and simulated values. It was possible to evaluate the impact of the soft bit estimation strategy and M$a$P decoding algorithms. It was also possible to evaluate the impact of the turbo decoding iterations and the different coding rates and the PB sizes defined in the IEEE 1901 standard.

6. **The integration of a communications infrastructure in a microgrids laboratory:** a near-real evaluation of a communications system in a microgrid context was performed using a laboratory infrastructure that was in part designed and implemented in the scope of this thesis. The implementation of an Ethernet based communications infrastructure allowed the emulation of uncertainties associated with the data exchange based on probabilistic models. This communications network allowed the support of different monitoring and control applications tailored for the microgrid operation. These were evaluated in near-real conditions with the participation of different controllable entities. A fully automated and configurable event generator platform was implemented to support the remote operation of the laboratory devices allowing the easy and fast deployment of specific operating scenarios. Using a set of simple control rules it was possible to demonstrate different strategies concerning the control of a microgrid both in interconnected and isolated scenarios. Results showed that despite the presence of delays the system response is typically shifted, whereas when losses occur significant system response deviation may occur mainly when operating in an emergency state. It was also possible to show the importance of local control strategies in allowing the system to operate within technical bounds despite the uncertainties in the set-point exchange mechanism associated with a central control strategy.

## 6.2 Open Topics and Future Work

There are some aspects related with the work developed and presented in this thesis that were not addressed given the limited time frame but are nevertheless important and relevant for the research in smart grids. It was decided not to explore them in more detail, because some were out of the initial scope while other topics have arisen with the natural progress of this thesis.

In what concerns the integrated models described and presented in this thesis, a more detailed functional and operational model can be established with the definition of more states and consequently more transitions according to the specific operation of each power system. As such, a more detailed set of information flows can be defined for both technical and market operation domains, allowing more detailed use-cases to be established with the necessary information exchange procedures to support each application. Since some information flows depend on the implemented ICT architecture that in turn depends on external definitions, imposed by regulatory agencies or by market vectors, such as cost, this will definitely be a recurrent topic in the next years.

The use of private or public communications networks is still an open issue and depending on the chosen implementation there are privacy and cyber-security issues to be accounted for, which were not addressed in this thesis. It is nevertheless necessary to ensure that the data exchanged through a shared communications medium or a shared communications network is protected against tampering, eavesdropping or any other technique that allows access to information by unauthorized entities, with the intention of causing malice or gain any sort of leverage, either technical or economical.

The candidate technologies to support the communications in private networks in the last-mile are mainly narrowed down to power line and wireless variants. The difficulties and limitations in conveying information using power lines outside buildings has motivated the appearance of hybrid approaches like IEEE 1901 and the implementation of narrowband alternatives like IEEE 1901.2. Although they intend to use a convenient infrastructure to convey data, the requirements imposed by the type of control applications considered in the scope of this thesis go beyond the targeted smart metering application, which can be difficult to meet in such a harsh environment. The use of the same medium to convey electricity and data means that when a fault occurs both electrical and data isolation take place. Given that wireless solutions have inherent difficulties in in-building environments a combination of broadband PLC and a wireless implementation can be explored as a cooperative communications solution for the last-mile. The effectiveness of this solution needs to be evaluated in the future.

The last-mile segment of smart grids represents an opportunity to explore the implementation of WMNs, which can greatly benefit from their specific characteristics. The absence of mobility and the fact that power constraints are typically not applicable, unless isolated operation is considered, allow a fairly stable set of communications scenarios to be established. Moreover the target use concerns mainly the outside building environment, which allows better propagation conditions. However, there are issues to address with the deployment of such networks in this context. Inherent to the wireless nature are interference, hidden and exposed node issues, which are aggravated by multi-hop implementations and need to be accounted for. The different node density in the last-mile segment can also introduce challenges in the control plane of a WMN, in terms of node discovery or topology refresh. The need of reconfiguring the logical topology due to the presence of obstacles or the degradation of the data link quality may introduce performance issues in time sensitive applications. An alternative to CSMA/CA can be thought in decoupling the control and data planes. More detailed propagation models can also be considered to evaluate the performance of the proposed WMN solution in deployment different scenarios, namely to accurately account for the impact of potential obstacles. More detailed propagation models can be used to evaluate the performance of the proposed WMN solution in the different scenarios, to account for the impact of potential obstacles.

Although the use of a scheduling mechanism based on polling eliminates issues like collisions in the data plane, inefficiencies arise with the increase in hop count as shown in the presented results. One particular inefficiency is associated with the lack of data to be exchanged with the GW, which means that resources are wasted to guarantee the opportunity to send data when there is none to be sent. Variants of polling that are able to adapt to different traffic patterns can be used to improve the network performance. In networks with a hop count higher than 3 or 4 spatial reuse techniques can be used as well to increase the network efficiency, which in turn could be complemented with frequency reuse strategies to reduce interference.

The use of relays as a way of extending the network coverage also introduces performance degradation due to the consequent increase in hop count. Thus, different strategies can be adopted in order to minimize the number of necessary relays in each network. However, the placement of relay nodes can also be used to provide the network with the necessary redundancy and flexibility in case of reconfiguration, which are typically approached in planning activities related with the actual implementation on the field. Furthermore, the use of relays can contribute positively when covering areas with different node density and to deal with obstacles that impair the physical connectivity. Overall, this can be formulated as an optimization problem that can be addressed from the physical or from the network point of view, which will involve multi-criteria techniques to be considered. This specific issue represents an interesting and challenging topic to be pursued.

The use of combined simulation tools represents a form of cooperatively integrating simulators for electric power systems and communications networks. Typically an association of simulators that were designed to operate separately is used along with coupling strategies that represent an overhead that impacts the overall system performance. In order to ensure that a fast simulation platform is capable of dealing with demanding application like those based on Monte Carlo techniques, an integrated design approach needs to be pursued, avoiding inefficient adaptations. The combined simulation can be explored as a tool to provide inputs for the planning activities of communications networks to deploy in last-mile while considering different scenarios.

The laboratory infrastructure represents a near-real microgrid environment equipped with a modular communications and control infrastructure that allows several research initiatives to be conducted. One of the important features of ns-3 is the emulation mode that allows the integration of network simulation with real communications network equipment. This functionality can be explored as a means of expanding the laboratory communications network beyond its limited physical implementation. The same rationale can be applied to the electric network where the combined use of simulators like Eurostag and the physical microgrid laboratory can foster the exploration of broader scenarios while allowing the assessment of prototypes or other equipment to be tested. This, combined with the use of power hardware-in-the-loop simulation techniques can allow the test of large and complex embedded systems in real-time in a near-real environment.

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# Appendix A

# Wireless Technologies Characteristics

Table A.1: Wireless Characteristics Consolidated by NIST

| Functionality/ Characteristic | Unit | EDGE | UMTS | HSPA+ | LTE | IEEE 802.11 | IEEE 802.16e |
|---|---|---|---|---|---|---|---|
| **Group 1: Link Availability** | | | | | | | |
| **Ability to reliably establish an appropriate device link** | % of time | Depends on deployment (typical > 99%) | Depends on deployment (typical > 99%) | Depends on deployment (typical > 99%) | Depends on deployment (typical > 99%) | 90% | Typically >99% |
| **Ability to maintain an appropriate connection** | failure rate per 1000 sessions | Depends on deployment (typ.<1%) | Depends on deployment (typ.<1%) | Depends on deployment (typ.<1%) | Depends on deployment (typ.<1%) | | 99% |
| **Group 2: Data/Media Type Supported** | | | | | | | |
| **Voice** | | Yes | Yes | Yes | Yes | Yes | Yes |
| **Data** | Max user data rate | 556.8 Kbps | 2.048 Mbps | 28 Mbps (Rel 7 Phy) | 300 Mbps DL (4x4); 75 Mbps UL (1x4) | 0.70 | 288.8 Mbps DL (4x4) 72.2 (1x4) |
| **Group 3: Coverage Area** | | | | | | | |
| **Geographic coverage area** | $km^2$ | 35 km radius normal; 120 km radius extended | 120 km radius for extended range cells | 120 km radius for extended range cells | 100 km radius | 0.79 | Optimized up to 5 km, functional up to 100 km |
| **Link budget** | dB | 146.36/ 133.39 dB (Veh A50) | Up to 147 dB | 135 dB for AMR 12.2 ( 6 Kbps at app layer) | Up to 143 dB DL; Up to 133 dB UL | 10.4 | DL 128.2 to 136.4 dB. UL 128.2 to 134.6 dB |

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**Table A.1 – continued from previous page**

| Functionality/ Characteristic | Unit | EDGE | UMTS | HSPA+ | LTE | IEEE 802.11 | IEEE 802.16e |
|---|---|---|---|---|---|---|---|
| **Group 4: Mobility** | | | | | | | |
| **Maximum relative movement rate** | km/h | 350 km/h | 350 km/h | 350 km/h | 350 km/h | 20 | 120 km/h |
| **Maximum Doppler** | Hz | 1000 with channel tracking equalizer | 648 | 648 | 648 | | 278 |
| **Group 5: Data Rates** | | | | | | | |
| **Peak over the air uplink data rate** | Mbps | 812.5 kbps | 1.024 Mbps | 11 Mbps for Rel 7 | 75 Mbps (1x4 MIMO) | 1 | 72.2 (1x4) |
| **Peak over the air downlink data rate** | Mbps | 812.5 kbps | 2.048 Mbps | 28 Mbps for Rel 7 | 300 Mbps (4x4 MIMO) | 1 | 288.8 Mbps DL ( 4x4) |
| **Peak goodput uplink data rate** | Mbps | 556.8 kbps | 0.960 Mbps | 9 Mbps | 63.75 Mbps | 0.70 | 72.2 Mbps |
| **Peak goodput downlink data rate** | Mbps | 556.8 kbps | 1.920 Mbps | 24 Mbps | 255 Mbps | 0.7 | 288.8 Mbps |
| **Group 6: RF Utilization** | | | | | | | |
| **Public radio standard operating in unlicensed bands** | GHz DL/UL | Yes, but not currently specified | Yes, but not currently specified | Yes, but not currently specified | Yes, but not currently specified. | Yes | Any unlicensed band below 6 GHz w/ interference mitigation |
| **Public radio standard operating in licensed bands** | GHz DL/UL | Multiple bands per 3GPP 45.005 | Multiple bands as per 3GPP 25.101 | Multiple bands as per 3GPP 25.101 | Multiple bands as per 3GPP 36.101 and 36.104 | No | Various |
| **Private radio standard operating in licensed bands** | GHz DL/UL | Can be operated, but not currently specified. | Can be operated, but not currently specified. | Can be operated, but not currently specified. | Can be operated, but not currently specified. | | Possible, e.g. 1.8 GHz in Canada |
| **Duplex method** | TDD/FDD | FDD | FDD and TDD | FDD and TDD | FDD and TDD | TDD | TDD and FDD |
| **Bandwidth** | kHz | 208 kHz @ 99% | 5 MHz for FDD | 5 MHz for FDD | 1.4, 3, 5, 10, 15, 20 MHz | 22000 | 3.5, 5, 7, 8.75, 10, 20 |
| **Spectral Efficiency** | bits/sec/Hz | 4.0625 | 0.2048 UL; 0.4096 DL | 2.2 UL; 5.6 DL | 3.75 UL; 15 DL | 0.045 | 14.44 DL; 3.61 UL |
| **Group 7: Data Frames and Packets** | | | | | | | |
| **Frame duration** | ms | 120/26 ms | 10 ms (2 ms TTI) | 10 ms (2 ms TTI) | 10 ms (1 ms TTI) | 18.4 ms | 2.5-20 ms |
| **Maximum packet size** | bytes | 1560 octets at RLC interface | No fixed size for FDD; TDD 12750 bytes | 42192 bits per stream DL; 22996 bits UL | 8188 bytes for DL/UL | 2300 | Max IP packet size: 1522 |
| **Segmentation support** | | Yes | Yes | Yes | Yes | Yes | Yes |
| **Group 8: Link Quality Optimization** | | | | | | | |
| **Diversity technique** | antenna, polarization, space, time | Yes | Yes | Yes | Yes | antenna | Antenna diversity, Space Time Block Codes, Spatial Multiplexing |

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**Table A.1 – continued from previous page**

| Functionality/ Characteristic | Unit | EDGE | UMTS | HSPA+ | LTE | IEEE 802.11 | IEEE 802.16e |
|---|---|---|---|---|---|---|---|
| **Beam steering** | | No | No (Rel 5) | Yes | Yes | No | Yes |
| **Retransmission** | | Yes | Yes | Yes | Yes | Yes | Yes |
| **Error correction technique** | | Punctured Conv. coding | Conv. and Turbo | Conv. and Turbo | Turbo; Tail Biting Conv. on BCH | No | RS Conv. Coding, Conv. Turbo Coding |
| **Interference cancellation** | | Yes | No (Rel 5) | Yes | Yes | No | Vendor specific |
| **Group 9: Radio Performance Measurement & Management** | | | | | | | |
| **RF frequency of operation** | | Multiple bands per 3GPP 45.005 | Specified in 3GPP 25.101 | Specified in 3GPP 25.101 | Specified in 3GPP 36.101 | 2.4 | Available band below 6 GHz |
| **Retries** | | Configurable | Configurable | Configurable | Configurable | Report Available | <= 4 |
| **RSSI** | | Yes | Yes | Yes | LTE RSRP and HSPA and EDGE RSSI | Report Available | RSSI and other measurements |
| **Lost packets** | | Residual BLER = 1% after HARQ | Residual BLER = 1% after HARQ | Residual BLER = 1% after HARQ | Residual BLER = 1% after HARQ | Report Available | Near zero in ARQ and HARQ |
| **Group 10: Power Management** | | | | | | | |
| **Mechanisms to reduce power consumption** | | Yes, e.g., DTX, DRX | Yes, e.g., DTX, DRX | Yes, e.g., DTX, DRX | Yes, e.g., DTX, DRX | Sleep mode | Sleep mode and Idle mode, Tx power control |
| **Low power state support** | | Yes | Yes | Yes, e.g., Longer DTX/DRX cycles | Yes | Yes | Sleep mode and Idle mode |
| **Group 11: Connection Topologies** | | | | | | | |
| **Point to point** | | Yes | Yes | Yes | Yes | Yes | Yes |
| **Point to Multipoint** | | Yes | Yes | Yes | Yes | Yes | Yes |
| **Broadcast** | | Yes | Yes | Yes | Yes | Yes | Yes |
| **Mesh** | | No | No | No | No | Yes | No |
| **Group 12: Connection Management** | | | | | | | |
| **Handover** | | Yes | Yes | Yes | Yes | Yes | Yes |
| **Media Access** | | Random and connection oriented | Random followed by connection oriented | Random and connection oriented | Random and connection oriented | CSMA | Coordinated contention and connection oriented |
| **Discovery** | | Sync and Broadcast channel | Sync and Broadcast channel | Sync and Broadcast channel | Sync and Broadcast channel | Yes | Autonomous |
| **Association** | | Temporary Block Flow (TBF) | Through various RNTIs | Through HRNTI and ERNTI assigned to UEs | Through CRNTI | Yes | Through SFID |

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**Table A.1 – concluded from previous page**

| **Functionality/ Characteristic** | **Unit** | **EDGE** | **UMTS** | **HSPA+** | **LTE** | **IEEE 802.11** | **IEEE 802.16e** |
|---|---|---|---|---|---|---|---|
| **Group 13: QoS and Traffic Prioritization** | | | | | | | |
| **Traffic priority** | diffserv, resserv | 3GPP priorities | 3GPP priorities | 3GPP priorities | 3GPP priorities | | Connection oriented QoS support |
| **Radio queue priority** | | Scheduler in base station | Yes at the Node B scheduler | Yes at the Node B scheduler | Yes at the Node B scheduler | Yes, 11e | Supported |

# Appendix B

# Use-Cases

This appendix presents the simplified market negotiation use-case, with the day-ahead and intra-day negotiations, along with the overall use-case, where a transition over all of different states of the functional and operational model. These use-cases are presented here, within the scope of the Chapter 3, to provide an understanding of the considered market negotiation information exchange.

The market operation involves the participation of aggregators as representatives of LV and MV customers in the market negotiation. The following use case details the message sequence considering a simplified day-ahead and intra-day negotiation. The day-ahead outcome will define the operating conditions for all participants in the distribution system for the following day, whereas the intra-day is triggered due to an insufficiency/disturbance in the daily operation that is addressed through market renegotiation.

The information exchange concerning the day-ahead market negotiation is illustrated in Fig. B.1 and the following sequence is considered:

1. In the day-ahead the request for bids is issued from the market to all participants;
2. The participating aggregators issue report requests to their customers' EB-LVs through the MGAU to assess the participation conditions, according to their controllable portfolio and respective availability;
3. The MGAU forwards the report requests from different aggregators to the respective LV EBs;
4. The report responses from EBs through MGAU allows the aggregators to collect information to forecast the needs and participation availability of their customers at LV level;
5. The MGAU forwards the report responses from different LV EBs to the respective aggregators;
6. Aggregators issue report requests to MV EBs through the RAU;
7. The RAU forwards the report requests to the respective MV EBs;
8. The MV EBs report back their availability and needs to their aggregators via RAU;
9. The RAU forwards the report responses from different MV EBs to the respective aggregators;

10. The aggregators present their bids to the market for all the periods for the following day;
11. The technical validation is requested by the market to the DMS;
12. The DMS requests a technical validation to CAMC for the MV networks;
13. The CAMC requests technical validation to the MGCCs under its supervision;
14. The MGGCs present their technical validation response of the respective LV networks to CAMCs;
15. The CAMCs present in turn the technical validation at the MV level to the DMS;
16. The DMS technically validates the market negotiated outcome;
17. The negotiation outcome is sent to aggregators, after the market is closed, with the respective results for all the periods of the following day;
18. The aggregators send set-points to MV EBs through RAU during the following day with the conditions for all periods to ensure that the negotiated conditions are fulfilled;
19. The RAU forwards the set-points to the respective MV EBs, of each aggregator;
20. The MV EBs confirm the reception of the set-points. This set-point confirmation can be used to convey a report information;
21. The aggregators send set-points to the LV EBs through the MGAU during the following day to ensure that the negotiated conditions are fulfilled;
22. The MGAU forwards the set-points to the respective LV EBs of each aggregator;
23. The set-points are acknowledged by EBs to MGAU;
24. In the intra-day negotiation a market request is initiated by the DSO control structure, in this case by the MGCC towards the DMS via the CAMC, to tackle a sudden event/disturbance that can be addressed by the market operation in the intra-day component. This request includes among other information the amount of power (consumed or injected) and the respective periods. It is assumed that the request is validated upstream in the system operator control hierarchy;
25. The CAMC validates and forwards to the DMS the market request by the MGCC;
26. The DMS informs the market of a request to address an operational issue under market operation;
27. The Market requests bids to involved aggregators operating in the MG area supervised by the issuing MGCC, since the conditions negotiated for the day-ahead are not met, given a deviation detected for the following periods of market operation;
28. Aggregators issue report requests to target EBs within the supervision of the MGCC via the MGAU;
29. The MGAU forwads the report requests from all aggregators to the respective customer, through the EB-LVs;

30. The target LV EBs report back with their availability according to the commercial agreement settled with their aggregator;
31. The MGAU forwards the incoming report responses from LV EBs to the respective aggregators;
32. The aggregators present their bids to the Market according to their forecast mechanisms and the market request conditions;
33. The Market informs the DMS of the results for the requested periods;
34. The DMS informs the MGCC of the market outcome via the respective CAMC;
35. The CAMC forwads the results to the MGCC and becomes aware of the decision;
36. The Market sends the results to the aggregators involved in the intra-day negotiation;
37. Agregators inform the LV EBs of their represented customers of the updated service conditions by issuing set-points for the negotiated periods via the MGAU;
38. The MGAU forwards the set-points of the involved aggregators to the respective LV EBs.

The all-state use case assumes that the system was operating in the normal mode of operation and a disturbance detected by the MGCC forces the system to enter the alarm state. The severity of the disturbance is increased, due to several possible reasons, resulting in a technical violation, thus leading to the activation of the emergency mode. A set-point exchange mechanism is triggered to address the disturbance and prepare the system, while in the resolution state, to return the normal mode of operation.

In this case, illustrated in Fig. B.2, it is assumed for simplicity that the information exchange reports (periodic or on-request) are not represented. Hence, it is assumed that in between some of the illustrated messages report requests are necessary in order to extract more information prior to issuing a particular message/order. A possible message sequence is depicted in Fig. B.2:

1. A disturbance is detected in a microgrid and the MGCC is aware of the fault occurrence. The MGCC informs the CAMC of the occurrence of the fault, which can have impact beyond the affected MG;
2. The DMS is informed by the CAMC of the disturbance occurrence in lower layers;
3. The MGAU is informed of the affected MG and is responsible for contacting the participating aggregators that have customers under their market control and supervision in the affected segment;
4. The potential aggregators are contacted by the MGAU, for the affected MG, with the necessary requests to handle the disturbance. It is assumed at this point that no technical requests are necessary;
5. Incoming set-points from aggregators are dispatched to the MGAU;
6. The MGAU informs the MGCCs of the resolution actions performed under market operation. The system operator managing and supervising entities, in this case the MGCC, continuously validate the operating conditions and are able to override any market decision in case more severe disturbance events occur, preventing if necessary the MGAU from dispatching set-points to EBs;

7. The MGAU issues set-points to the respective EBs represented by aggregators with the necessary information to allow their participation in mitigating or solving the disturbance;
8. A new disturbance is detected or there was an aggravation of the technical operating conditions, with a technical violation within the MG and, as such, the MGCC notifies the CAMC;
9. The DMS is notified by the CAMC of the aggravation of the operating conditions;
10. The MGAU is notified of the technical operating conditions and the consequent market operation suspension and the instantiation of the emergency operation;
11. The affected aggregators are informed of the market operation suspension and the reasons of the suspension and the consequent inability of the system to ensure a normal operation;
12. The MGCC issues set-points to EBs via the MGAU in order to deal with the aggravated operating conditions ;
13. The set-points are dispatched to the respective EBs. Additional supervisory and control information requests may be issued (periodically or per-request);
14. The system operating conditions are recovered and the MGCC notifies the CAMC that the MG is able to operate in normal conditions;
15. The DMS is notified via CAMC of the disturbance clearance and, as such, it can initiate the necessary mechanisms towards the restoration of the normal operation via a resolution operation mode;
16. The MGAU is updated with the operating conditions and the possibility of returning to market operation;
17. The DMS issues a market request with the necessary technical operation conditions to ensure the transition to the normal operation;
18. The Market requests bids from potentially participating aggregators, assuming that it is no longer possible to maintain the previous day negotiated condition thus leading to an intra-day market negotiation process;
19. Aggregators assess the availability of their representatives, from a contractual and operational perspective, issuing availability requests via MGAU. This will allow aggregators to participate in the bidding process;
20. The MGAU forwards the availability requests to the proper EBs;
21. The contacted EBs report to the MGAU their availability in terms of available controllable portfolio, under the contracted services with their aggregators. The smart charging can be seen here as an example of such contractual participation of customers;
22. Aggregators are informed of the availability of their representatives and accordingly decide to present their bids to the market;

23. Aggregators present their bids to the market under the intra-day negotiation;
24. The Market requests a technical validation of the negotiated market bids to the DMS;
25. The DMS request validation from lower CAMCs;
26. Each CAMC requests validation from the involved MGCCs;
27. MGCCs validate the market conditions and their technical feasibility;
28. The DMS is informed of the validation results from lower layers;
29. The Market is made aware of the validation outcome;
30. The Market informs all the involved aggregators in the negotiation process of the achieved outcome, as well as the system operator. If no further market negotiation is needed the system returns to the normal mode of operation;
31. Aggregators exchange set-points with their customers via the MGAU;
32. Customers receive set-points for the next periods under normal (market) operation.

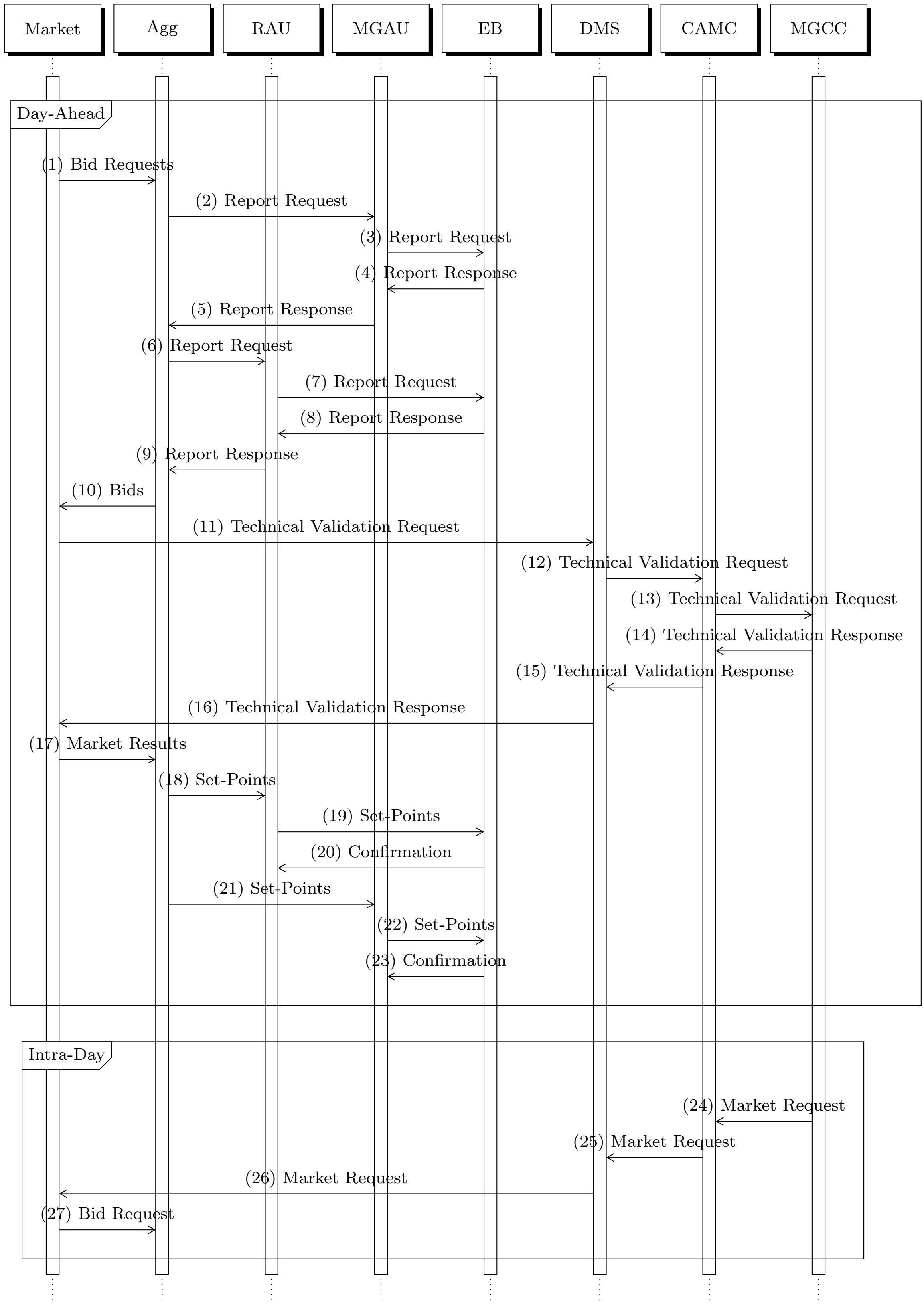


Figure B.1: Market Negotiation

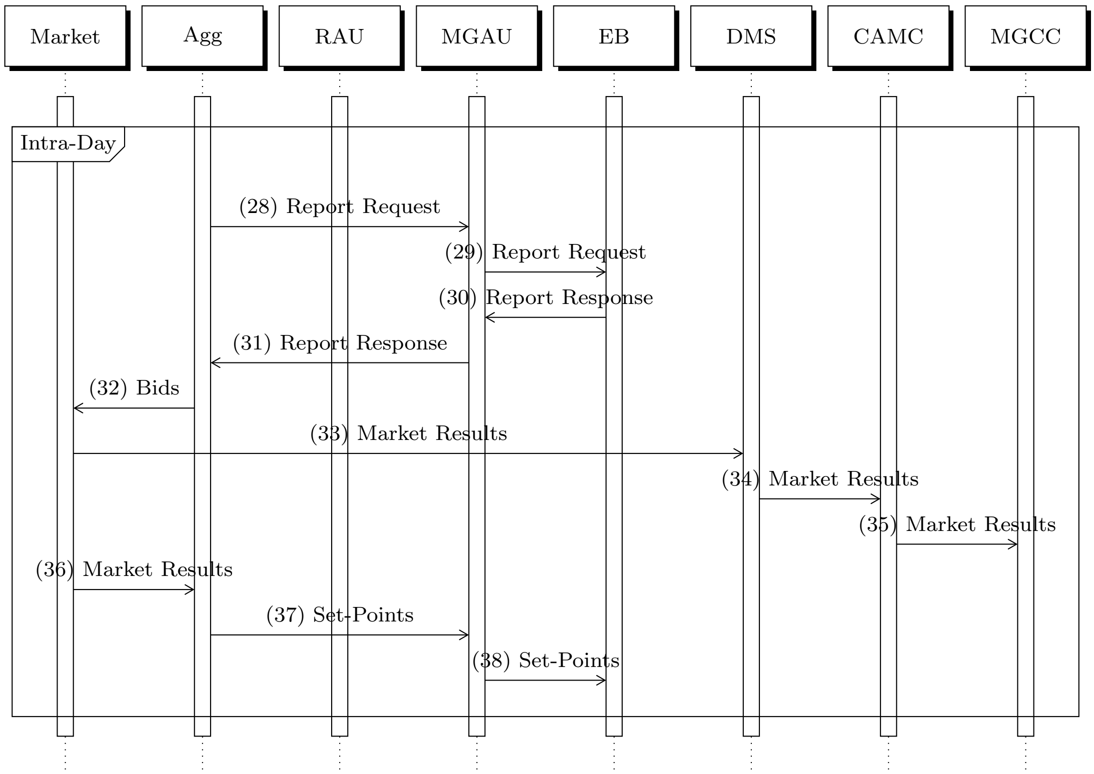


Figure B.1: Market Negotiation (cont.)

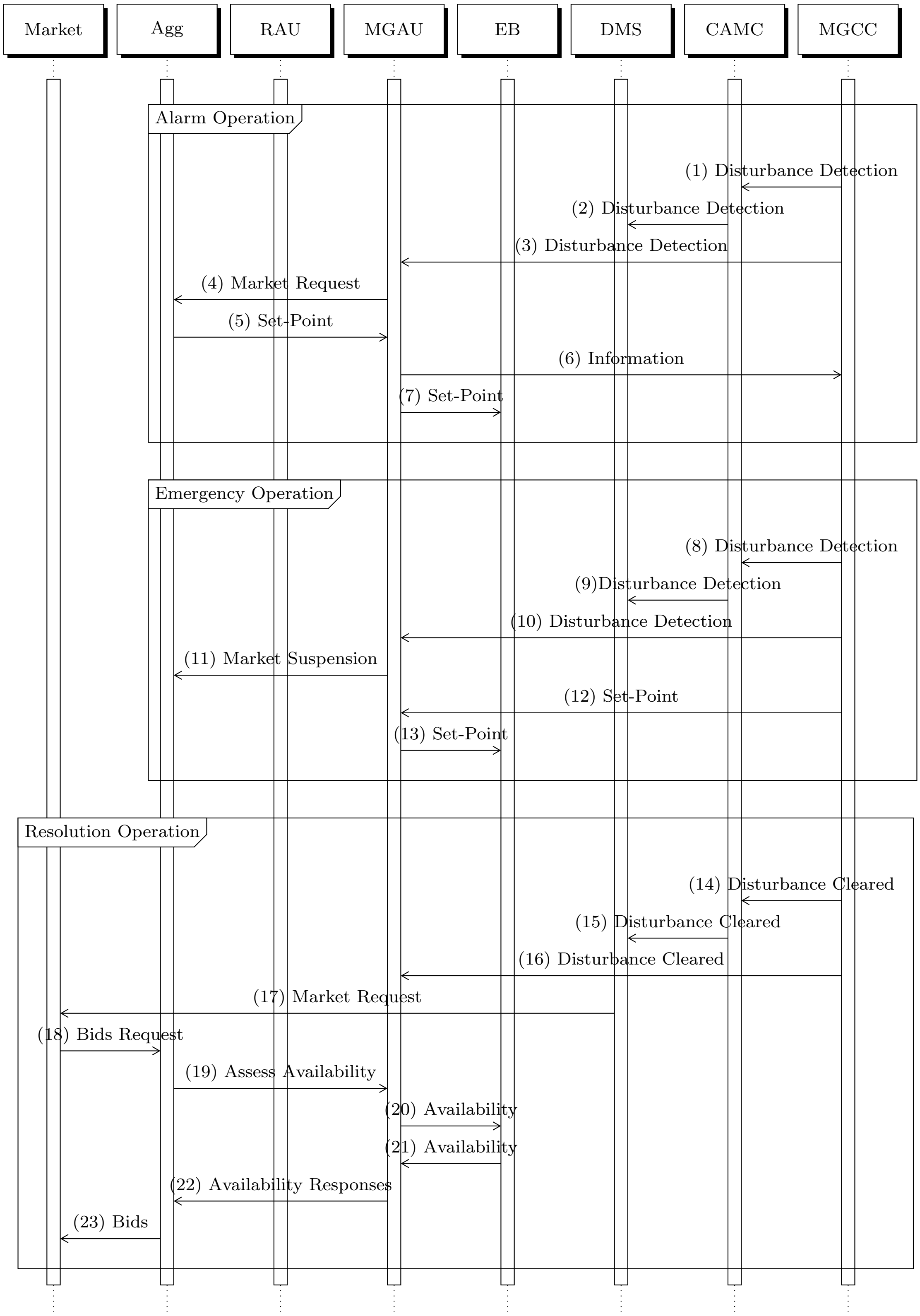


Figure B.2: All State Operation

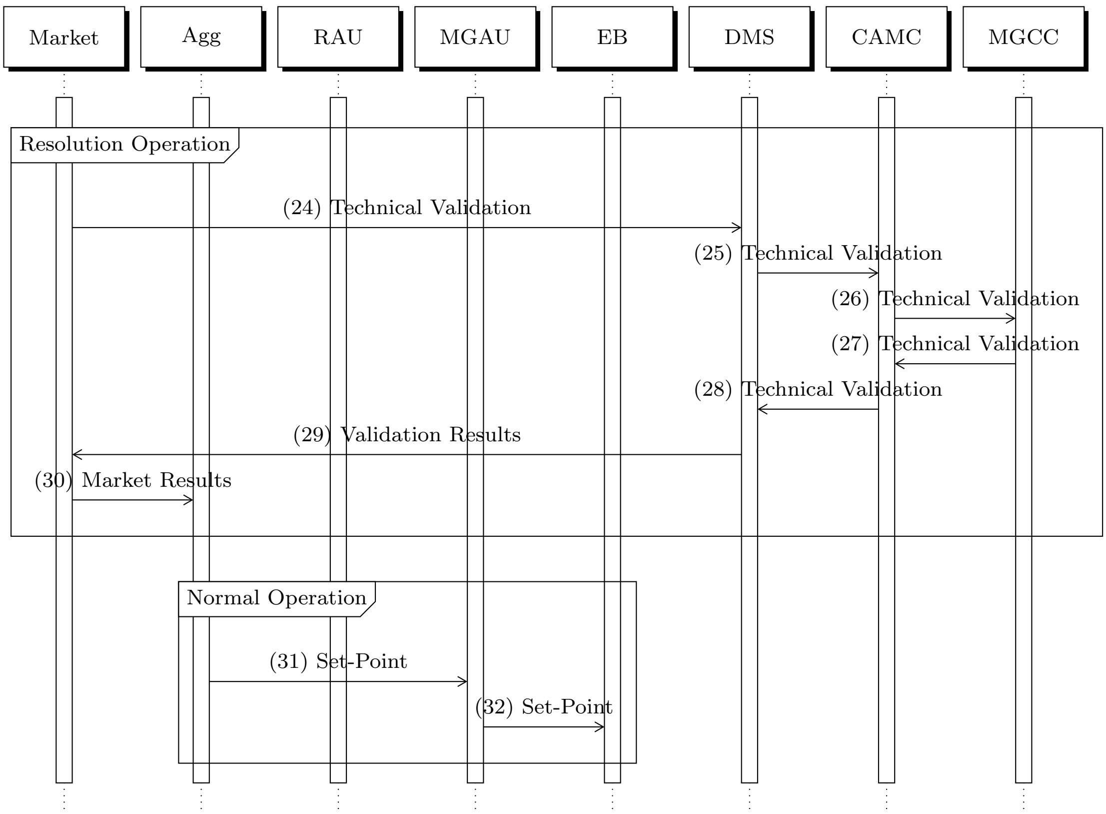


Figure B.2: All State Operation (cont.)

# Appendix C

# Test Network Parameters

This appendix details the parameters for both the electromechanical models and for the secondary control scheme that were used in the test network presented in Section 5.2.

## C.1 Parameters of the Electromechanical Models

The electromechanical models used for the different components of the network are based on those presented in and [4] and extended in [36] where a more detailed explanation can be found, namely in terms of its implementation in Eurostag with the respective macroblock definition.

### C.1.1 Diesel Unit

Table C.1: Diesel Motor

| **Parameter** | **Value** | **Description** |
|---:|---:|---:|
| R (p.u.) | 0.05 | Permanent speed droop |
| $K_I$ (p.u.) | 2.5 | Proportional gain |
| $P_{max}$ (p.u.) | 1.0 | Maximum output power |
| $P_{min}$ (p.u.) | 0.0 | Minimum output power |
| $T_h$ (s) | 0.1 | Control time constant |
| Tg (s) | 1.0 | Motor time constant |

Table C.2: Diesel Synchronous Machine

| **Parameter** | **Value** | **Description** |
|:---:|---:|:---:|
| $S_n$ (MVA) | 1.5 | Rated apparent power |
| $V_n$ (kV) | 15 | Base voltage machine side |
| $R_s$ (p.u.) | 0.0 | Stator resistance |
| $X_l$ (p.u.) | 0.01 | Stator leakage |
| $X_d$ (p.u.) | 1.45 | Direct reactance |
| $X_q$ (p.u.) | 1.45 | Quadrature reactance |
| $X'_d$ (p.u.) | 0.25 | Direct transient reactance |
| $T'_d$ (p.u.) | 4.47 | Direct transient time constant |
| H (s) | 9.0 | Constant of inertia |

### C.1.2 Combined Heat and Power Unit

Table C.3: Steam Turbine

| Parameter | Value | Description |
|---|---|---|
| $F_{HP}$ (p.u.) | 0.3 | Fraction of total power generated by the high pressure section |
| $L_{C_1}$ (p.u.) | 0.3 | Rate limit (opening) |
| $L_{C_2}$ (p.u.) | -1.0 | Rate limit (closing) |
| $KL_G$ (p.u.) | 25 | Governor droop |
| $T_{CH}$ (s) | 0.3 | Time constant of main inlet volume and steam chest |
| $T_{RH}$ (s) | 5.0 | Time constant of reheater |
| $T_{SM}$ (s) | 0.3 | Time constant of servomotor |
| $T_{SR}$ (s) | 0.1 | Time constant of speed relay |

Table C.4: CHP Synchronous Machine

| Parameter | Value | Description |
|---|---|---|
| $S_n$ (MVA) | 2.2 | Rated apparent power |
| $V_n$ (kV) | 15 | Base voltage machine side |
| $R_s$ (p.u.) | 0.0 | Stator resistance |
| $X_l$ (p.u.) | 0.01 | Stator leakage |
| $X_d$ (p.u.) | 2.73 | Direct reactance |
| $X_q$ (p.u.) | 2.73 | Quadrature reactance |
| $X'_d$ (p.u.) | 0.31 | Direct transient reactance |
| $T'_d$ (p.u.) | 4.47 | Direct transient time constant |
| H (s) | 4.9 | Constant of inertia |

### C.1.3 Hydro Unit

Table C.5: Hydro Turbine

| Parameter | Value | Description |
|---|---|---|
| $g_{NL}$ | 0.16 | Gate opening at no load |
| $g_{FL}$ | 0.96 | Gate opening at full load |
| $H_0$ (s) | 1 | Steady state constant of inertia |
| $T_W$ (s) | 1.15 | Hydraulic response time at full load |

Table C.6: Hydro Asynchronous Machine

| Parameter | Value | Description |
|---|---|---|
| $S_n$ (MVA) | 2.8 | Rated apparent power |
| $V_n$ (kV) | 15 | Base voltage machine side |
| H (s) | 6.0 | Constant of inertia |
| $L_{LR}$ (p.u.) | 0.1257 | Leakage reactance winding 1 |
| $L_{LS}$ (p.u.) | 0.0953 | Stator leakage reactance |
| $L_M$ (p.u.) | 3.93 | Rotor-stator mutual reactance |
| $R_R$ (p.u.) | 0.01219 | Leakage resistance winding 1 |
| $R_S$ (p.u.) | 6.7246e-03 | Stator leakage resistance |

### C.1.4 Microturbine

Table C.7: Microturbine

| Parameter | Value | Description |
|---|---|---|
| $K_T$ | 1 | Proportional gain of the temperature control |
| $K_P$ | 1 | Proportional gain of the output power controller |
| $K_I$ | 1.08 | Integral gain of the output power controller |
| $T_1$ (s) | 10 | Feed-in time constant |
| $T_2$ (s) | 0.1 | Feed-in time constant |
| $T_3$ (s) | 3 | Load limiter time constant |
| $V_{max}$ | 1.2 | Valve max position |
| $V_{min}$ | -0.1 | Valve min position |
| $L_{max}$ | 1.2 | Load limit |

Table C.8: Microturbine Synchronous Machine

| Parameter | Value | Description |
|---|---|---|
| $U_n$ (V) | 400 | Nominal voltage |
| $I_n$ (A) | 36 | Nominal current |
| $P_n$ (kW) | 30 | Nominal power |
| J ($Kg.m^2$) | 0.003 | Combined rotor and load inertia |
| p | 2 | Number of pairs of poles |
| F | 5.00E-07 | Friction factor |
| $\Phi_m$ (Wb) | 0.0534 | Permanent mangets induced flux |
| $L_d$ (mH) | 6.875E-01 | Direct inductance |
| $L_q$ (mH) | 6.875E-01 | Quadrature inductance |
| $R_s$ ($\Omega$) | 0.25 | Stator leakage resistance |

### C.1.5 Fuel Cell

Table C.9: Fuel Cell

| Parameter | Value | Description |
|---|---|---|
| $P_n$ (kW) | 100 | Nominal power |
| $K_{H_2}$ | 0.843 | Valve molar constant for hydrogen |
| $K_{H_20}$ | 0.281 | Valve molar constant for water |
| $K_{O_2}$ | 2.52 | Valve molar constant for oxygen |
| $N_0$ | 384 | Number of cells in the stack |
| r ($\Omega$) | 0.126 | Internal resistance |
| Te (s) | 0.8 | Electrical response time constant |
| TFP (s) | 5 | Fuel reformer time constant |
| $T_{H_2}$ (s) | 26.1 | Hydrogen flow time constant |
| $T_{H_20}$ (s) | 78.3 | Water vapor flow time constant |
| $T_{O_2}$ (s) | 2.91 | Oxygen flow time constant |
| $U_{max}$ | 0.9 | Maximum fuel utilization |
| $U_{min}$ | 0.8 | Minimum fuel utilization |
| $U_{opt}$ | 0.85 | Optimal fuel utilization |
| $V_{IN}$ (V) | 343.8 | Cells internal voltage |

### C.1.6 Voltage Source Inverter

Table C.10: Voltage Source Inverter

| Parameter | Value | Description |
|---|---|---|
| Pn (kW) | 150 | Nominal power |
| $K_{I_P}$ | 1 | Active power controller integral gain |
| $K_{P_P}$ | 1 | Active power controller proportional gain |
| R | 0.02 | Speed droop |
| $K_V$ | -3 | Reactive power gain |
| $T_{D_P}$ (s) | 2 | Active power control time constant |
| $T_{D_Q}$ (s) | 1 | Reactive power control time constant |
| $T_{SET}$ (s) | 0.1 | External control time constant |
| X | 0.25 | Internal reactance |
| $f_{DB_{min}}$ (Hz) | 49.8 | Minimum frequency deadband |
| $f_{DB_{max}}$ (Hz) | 50.2 | Maximum frequency deadband |

### C.1.7 Wind Units

Table C.11: Wind Turbines

| Parameter | Micro | Mini | Description |
|---|---|---|---|
| $P_n$ (MW) | 0.04 | 2 | Nominal Power |
| $Rot_D$ (m) | 18 | 75 | Rotor diameter |
| $Rot_s$ (r.p.m.) | 55 | 18 | Rated rotor speed |
| $W_s$ (m/s) | 11 | 12 | Wind speed |
| $W_{cs}$ (m/s) | 3 | 3.5 | Cut-in wind speed |

Table C.12: Wind Asynchronous Machines

| Parameter | Micro | Mini | Description |
|---|---|---|---|
| $P_n$ (kW) | 15 | 2000 | Nominal power |
| $V_b$ (V) | 400 | 690 | Nominal voltage |
| $f_n$ (Hz) | 50 | 50 | Nominal frequency |
| p | 2 | 4 | Number of pairs of poles |
| H (s) | 3.5 | 3.5 | Constant of inertia |
| $L_{LR}$ (p.u.) | 0.0991 | 0.1257 | Rotor leakage reactance |
| $L_{LS}$ (p.u.) | 0.0991 | 0.0953 | Stator leakage reactance |
| $R_R$ (p.u.) | 0.02205 | 0.0121884 | Rotor leakage resistance |
| $R_S$ (p.u.) | 0.02147 | 6.7246E-03 | Stator leakage resistance |

## C.2 Parameters of the Secondary Control Scheme

The parameters for each of the different participating units of the secondary control scheme are presented in the following tables. In Table C.13 are the parameters of the potentially MV controllable elements, including both generators and MGs. Table C.14 presents the parameters of the potentially controllable loads, which include those installed at MV and those associated with each MG, aggregated. Tables C.15 and C.16 detail the parameters of the two types of MGs used in the test network: type 1 (MG01 - MG12), type 2 (MG13 - MG17).

Table C.13: Parameters of MV Controllable Entities

| ID | LimMin | LimMax | StartCost | RunCost | Delay | MGCC | Adjust | Factor | MinVar |
|---:|---:|---:|---:|---:|---:|---:|---:|---:|---:|
| MGCC01 | 0 | 1 | 5 | 11 | 2 | 1 | 1 | 1 | 0.01 |
| MGCC02 | 0 | 1 | 5 | 15 | 2 | 1 | 1 | 1 | 0.01 |
| MGCC03 | 0 | 1 | 5 | 14 | 2 | 1 | 1 | 1 | 0.01 |
| MGCC04 | 0 | 1 | 5 | 11 | 2 | 1 | 0 | 1 | 0.01 |
| MGCC05 | 0 | 1 | 5 | 14 | 2 | 1 | 0 | 1 | 0.01 |
| MGCC06 | 0 | 1 | 5 | 14 | 2 | 1 | 0 | 1 | 0.01 |
| MGCC07 | 0 | 1 | 5 | 14 | 2 | 1 | 0 | 1 | 0.01 |
| MGCC08 | 0 | 1 | 5 | 15 | 2 | 1 | 0 | 1 | 0.01 |
| MGCC09 | 0 | 1 | 5 | 15 | 2 | 1 | 0 | 1 | 0.01 |
| MGCC10 | 0 | 1 | 5 | 15 | 2 | 1 | 0 | 1 | 0.01 |
| MGCC11 | 0 | 1 | 5 | 15 | 2 | 1 | 0 | 1 | 0.01 |
| MGCC12 | 0 | 1 | 5 | 15 | 2 | 1 | 0 | 1 | 0.01 |
| MGCC13 | 0 | 1 | 5 | 14 | 2 | 1 | 1 | 1 | 0.01 |
| MGCC14 | 0 | 1 | 5 | 15 | 2 | 1 | 1 | 1 | 0.01 |
| MGCC15 | 0 | 1 | 5 | 15 | 2 | 1 | 1 | 1 | 0.01 |
| MGCC16 | 0 | 1 | 5 | 15 | 2 | 1 | 0 | 1 | 0.01 |
| MGCC17 | 0 | 1 | 5 | 15 | 2 | 1 | 0 | 1 | 0.01 |
| HYDRO | 0 | 1 | 10 | 10 | 2 | 0 | 0 | 100 | 0.01 |
| CHP | 0.1 | 1 | 10 | 19 | 2 | 0 | 1 | 100 | 0.01 |
| CHPA | 0.1 | 1 | 10 | 20 | 2 | 0 | 1 | 100 | 0.01 |

Table C.14: Parameters of Controllable Loads

| Node | LimMin | LimMax | StartCost | RunCost | MGCC | Adjust | MinVar | ShedLevels |
|---:|---:|---:|---:|---:|---:|---:|---:|---:|
| 2143 | 0 | 0.35 | 10 | 21 | MGCC01 | 1 | 0.01 | 5 |
| 2141 | 0 | 0.4 | 10 | 21 | MGCC02 | 1 | 0.01 | 5 |
| 2144 | 0 | 0.1 | 10 | 21 | MGCC03 | 1 | 0.01 | 5 |
| 2142 | 0 | 0.35 | 10 | 21 | MGCC04 | 0 | 0.01 | 5 |
| 2160 | 0 | 0.05 | 10 | 22 | MGCC05 | 0 | 0.01 | 5 |
| 2161 | 0 | 0.15 | 10 | 22 | MGCC06 | 0 | 0.01 | 5 |
| 2116 | 0 | 0.19 | 10 | 22 | MGCC07 | 0 | 0.01 | 5 |
| 2169 | 0 | 0.08 | 10 | 23 | MGCC08 | 0 | 0.01 | 5 |
| 2170 | 0 | 0.19 | 10 | 21 | MGCC09 | 0 | 0.01 | 5 |
| 2113 | 0 | 0.1 | 10 | 21 | MGCC10 | 0 | 0.01 | 5 |
| 2186 | 0 | 0.13 | 10 | 22 | MGCC11 | 0 | 0.01 | 5 |
| 3157 | 0 | 0.35 | 10 | 22 | MGCC12 | 0 | 0.01 | 5 |
| NLV1 | 0 | 0.2 | 10 | 21 | MGCC13 | 1 | 0.01 | 5 |
| NLV2 | 0 | 0.35 | 10 | 22 | MGCC14 | 1 | 0.01 | 5 |
| NLV3 | 0 | 0.2 | 10 | 23 | MGCC15 | 1 | 0.01 | 5 |
| NLV5 | 0 | 0.19 | 10 | 22 | MGCC16 | 0 | 0.01 | 5 |
| NLV4 | 0 | 0.19 | 10 | 21 | MGCC17 | 0 | 0.01 | 5 |
| NCHP | 0 | 0.7 | 10 | 22 | (NONE) | 1 | 0.01 | 8 |
| CHPA | 0 | 0.5 | 10 | 21 | (NONE) | 1 | 0.01 | 8 |
| 3252 | 0 | 0.11 | 10 | 22 | (NONE) | 1 | 0.01 | 8 |
| 1123 | 0 | 0.2 | 10 | 20 | (NONE) | 1 | 0.01 | 8 |
| 1279 | 0 | 0.25 | 10 | 24 | (NONE) | 1 | 0.01 | 8 |
| 3549 | 0 | 0.11 | 10 | 23 | (NONE) | 1 | 0.01 | 8 |
| 3259 | 0 | 0.13 | 10 | 24 | (NONE) | 1 | 0.01 | 8 |
| 1275 | 0 | 0.13 | 10 | 26 | (NONE) | 1 | 0.01 | 8 |
| 3566 | 0 | 0.27 | 10 | 28 | (NONE) | 1 | 0.01 | 8 |
| 3565 | 0 | 0.27 | 10 | 21 | (NONE) | 1 | 0.01 | 8 |
| 1482 | 0 | 0.13 | 10 | 22 | (NONE) | 0 | 0.01 | 8 |
| 3198 | 0 | 0.2 | 10 | 21 | (NONE) | 0 | 0.01 | 8 |
| 3199 | 0 | 0.2 | 10 | 22 | (NONE) | 1 | 0.01 | 8 |
| 3200 | 0 | 0.2 | 10 | 23 | (NONE) | 1 | 0.01 | 8 |
| 1441 | 0 | 0.13 | 10 | 26 | (NONE) | 0 | 0.01 | 8 |

Table C.15: Parameters of LV MG - type 1

| ID | LimMin | LimMax | StartCost | RunCost | Adjust | MinVar |
|---:|---:|---:|---:|---:|---:|---:|
| PV1 | 0 | 1 | 5 | 10 | 1 | 0.01 |
| MTA1 | 0.1 | 1 | 5 | 10 | 1 | 0.01 |
| VSI1 | 0 | 1 | 5 | 12 | 0 | 0.01 |
| FC1 | 0.1 | 1 | 5 | 11 | 0 | 0.01 |
| MTB1 | 0.1 | 1 | 5 | 10 | 1 | 0.01 |

Table C.16: Parameters of LV MG - type 2

| ID | LimMin | LimMax | StartCost | RunCost | Adjust | MinVar |
|---:|---:|---:|---:|---:|---:|---:|
| PV13 | 0 | 1 | 5 | 10 | 1 | 0.01 |
| DFA13 | 0 | 1 | 5 | 10 | 1 | 0.01 |
| VSI13 | 0 | 1 | 5 | 12 | 0 | 0.01 |
| FC13 | 0.1 | 1 | 5 | 11 | 0 | 0.01 |
| DFB13 | 0 | 1 | 5 | 10 | 1 | 0.01 |

# Appendix D

# Distribution Feeders

This appendix presents the graphic representation of the LV and MV electric distribution feeders analyzed from the information provided by EDPD, the Portuguese DSO, as described in Sections 4.3 and 5.3.

## D.1 Low Voltage Feeders

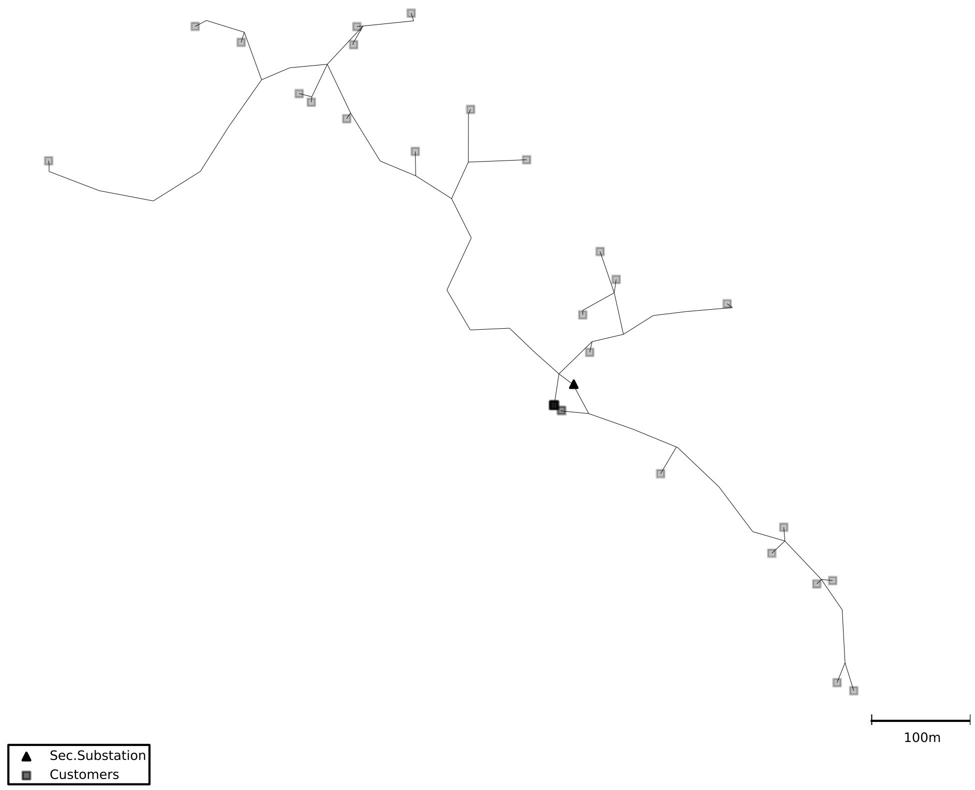


Figure D.1: Rural LV Feeder

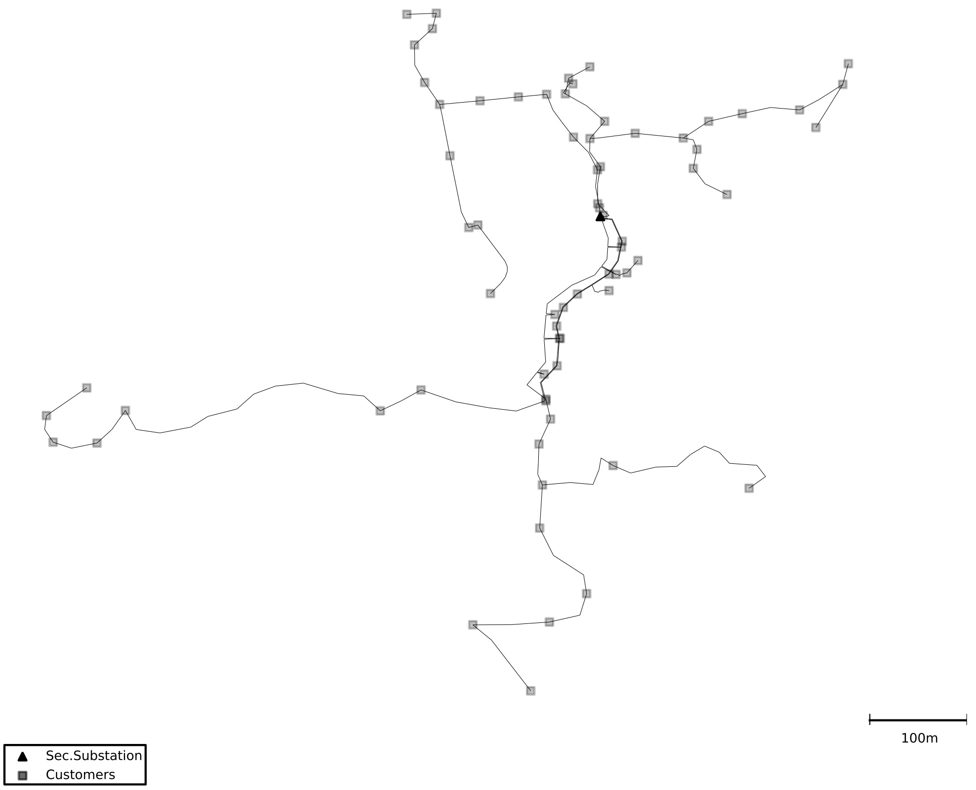


Figure D.2: Mixed LV Feeder

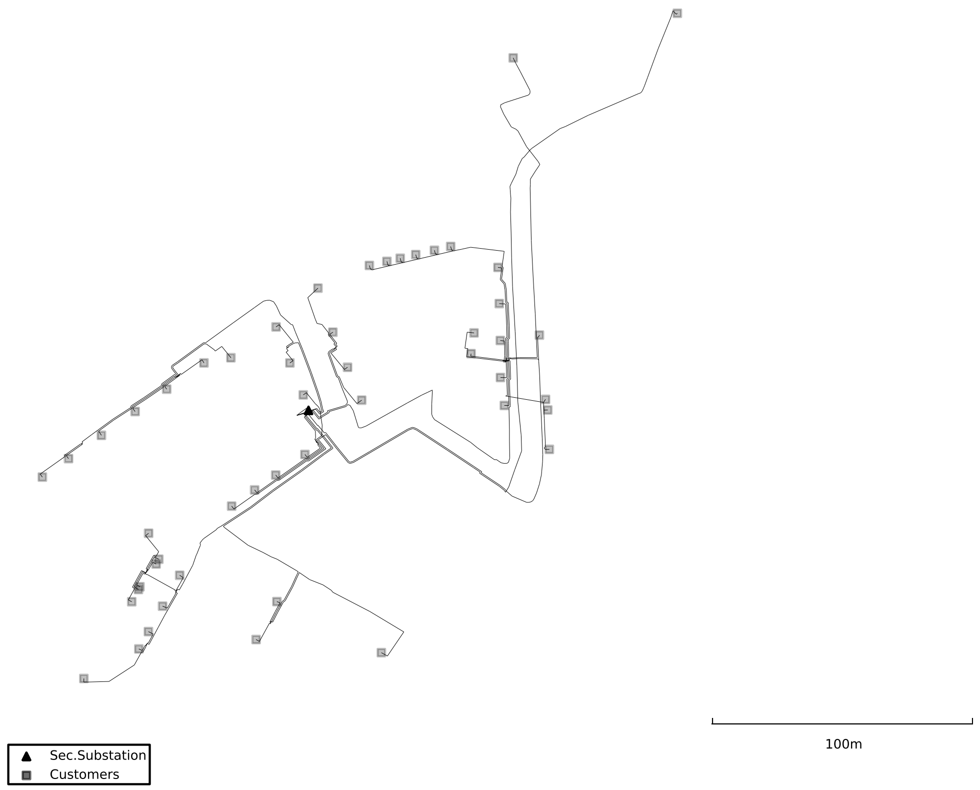


Figure D.3: Urban LV Feeder

## D.2 Medium Voltage Feeders

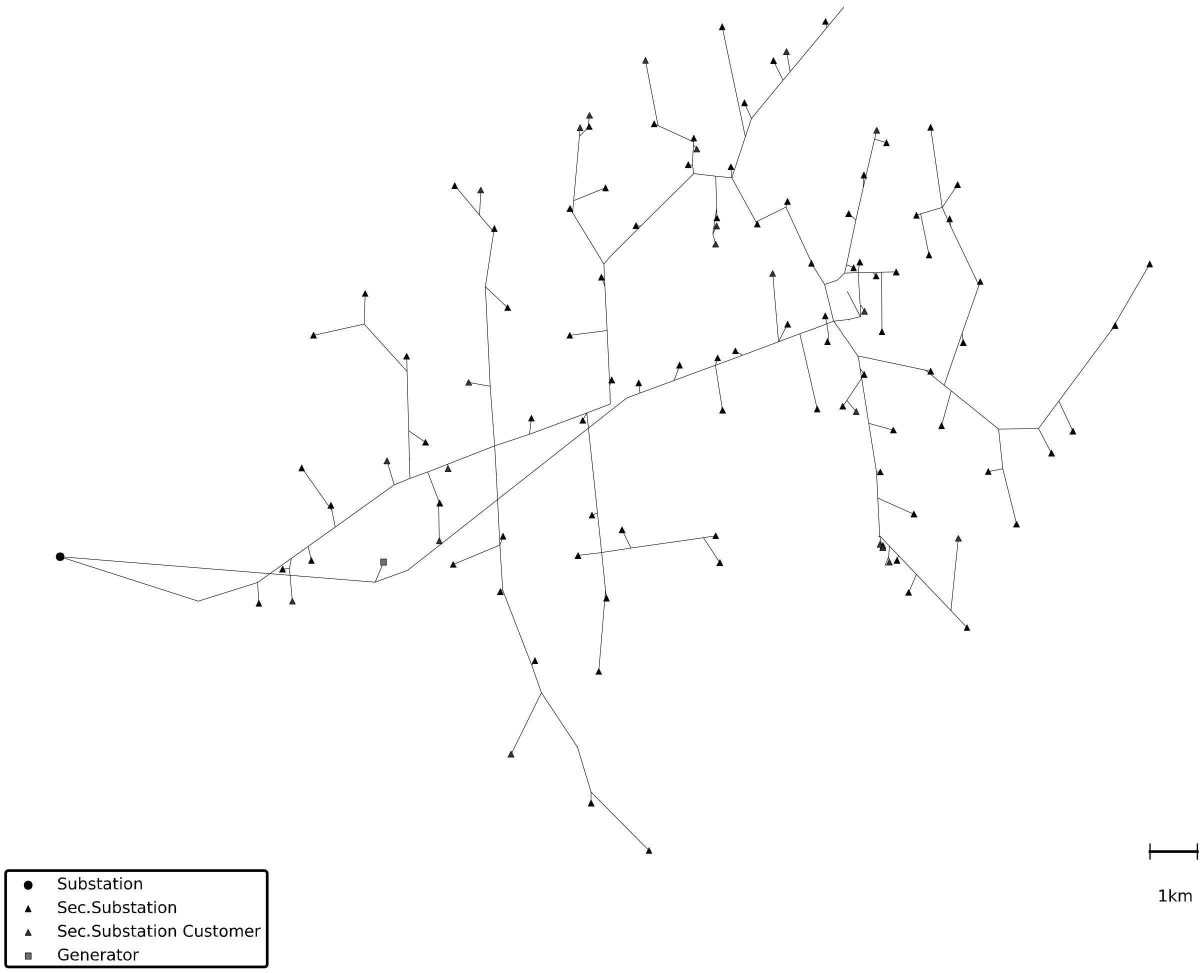


Figure D.4: Rural MV Feeder

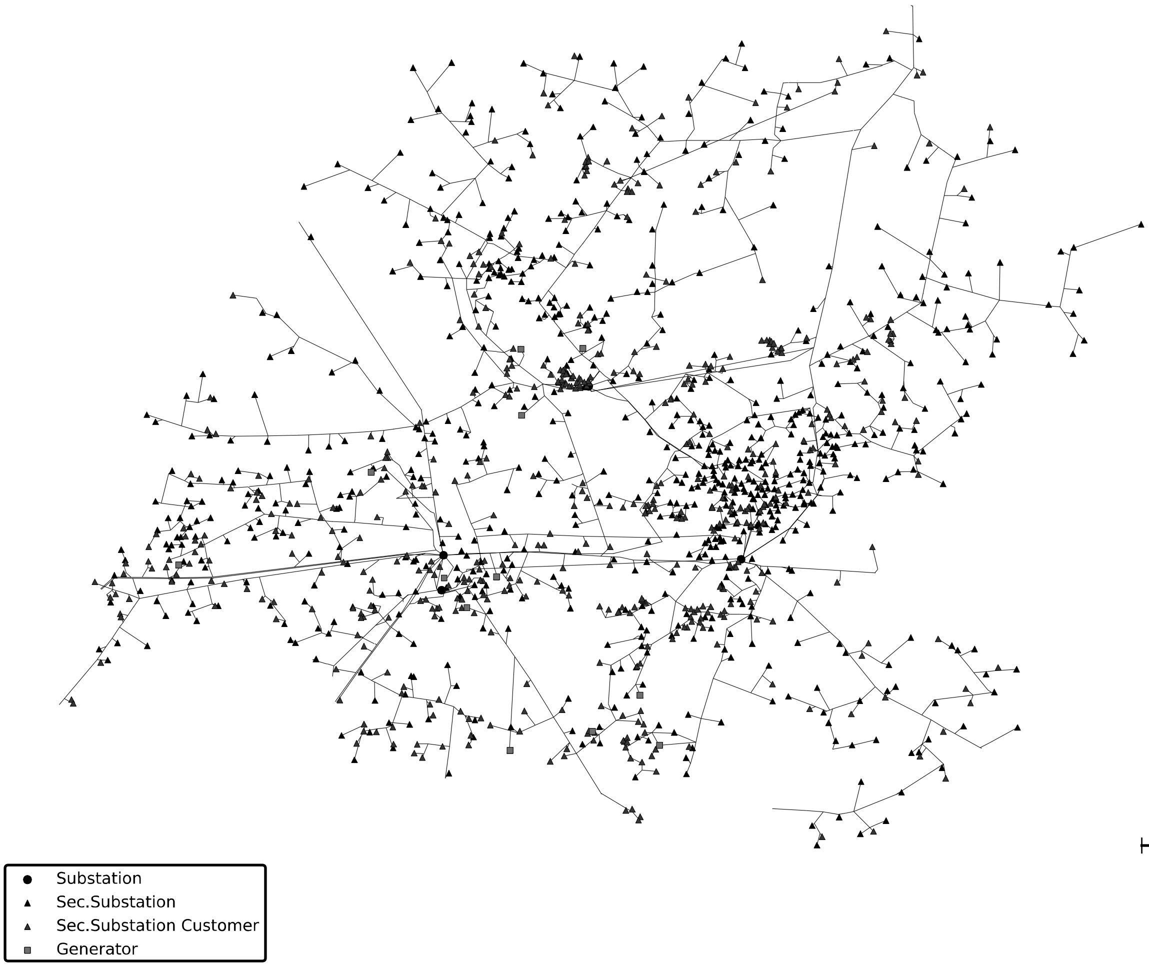


Figure D.5: Mixed MV Feeder


Figure D.6: Urban MV Feeder

# Appendix E

# Soft Bit Calculation

This appendix expands the soft bit calculation procedures for square constellations from 16-QAM to 256-QAM used in the implementation of the de-mapper block, presented in Section 4.5.1, specifically designed in accordance with the IEEE 1901 standard. The formulation presented here is related with a particular case of signal detection over a Gaussian channel, which is often designated as binary detection, where after receiving a bit sequence subjected to noise an estimation procedure will try to guess the originally sent sequence. The basics on this topic and a more detailed explanation can be found on existing literature, for example in [130, 131, 146].

It is assumed here that $\mathbf{y}$ is a encoded sequence received through a noisy medium. For each subcarrier $c$ and encoded sequence can be independently defined as $\mathbf{y}_c = \mathbf{x}_c + \mathbf{n}$, being $\mathbf{x}_c$ the encoded transmitted signal and $n$ the additive noise from the channel. For simplicity it is assumed the generic representation over a subcarrier without explicitly using the subscript $c$, since the procedure described here can be applied independently to the received signals in each subcarrier.

The signal detection procedure involves a decision about the received sequence according to the supposedly transmitted one. As such there is an associated probability of error that should be minimized. The minimization of this probability is achieved with the maximum *a posteriori* (MAP) decision rule, which is defined as:

$$\hat{\mathbf{x}} = \arg\max_{s \in \mathcal{S}} p(\mathbf{y}|\mathbf{x} = s), \text{ where } \mathcal{S} = \{(I_i, Q_i), i = 0, \ldots, M-1\} \tag{E.1}$$

Hence, the estimate $\hat{\mathbf{x}}$ is determined by the maximum $p(\mathbf{y}|\mathbf{x})$, which is the probability density function of the received sequence $\mathbf{y}$ when the transmitted sequence $\mathbf{x}$ is one of the $s$ points of the constellation $\mathcal{S}$. The in-phase, $I_i$, and quadrature, $Q_i$, components of each of the $M$ symbols is composed of a finite number of bits, $b_k$, that depend on the modulation scheme used in the transmission process.

For the case of binary detection the Log-Likelihood Ratio (LLR) is typically the metric considered when deciding over the received signal. The use of LLR, or *"log of probabilities"* as it is often designated, is mainly due to implementation reasons. It is used given the simplicity in processing sums instead of products, the fact that is it often used in the decoder stages, and to limit underflow problems that might occur due to very small variations introduced by the Gaussian distribution, as explained in [147], which in this case are associated with the noise component $n$.

Considering the Bayes theorem the conditional probabilities in the LLR can be expressed as:

$$\Lambda(b_k|\mathbf{y}) = \log \frac{p(b_k = 1|\mathbf{y})}{p(b_k = 0|\mathbf{y})} = \log \frac{p(\mathbf{y}|b_k = 1) \cdot p(b_k = 1)}{p(\mathbf{y}|b_k = 0) \cdot p(b_k = 0)}, \tag{E.2}$$

Assuming that the bits are equally likely to be sent, $P(b_k = 1) = P(b_k = 0)$:

$$\Lambda(b_k|\mathbf{y}) = \log \frac{p(b_k = 1|\mathbf{y})}{p(b_k = 0|\mathbf{y})} = \log \frac{p(\mathbf{y}|b_k = 1)}{p(\mathbf{y}|b_k = 0)} \tag{E.3}$$

If a decision is to be produced immediately after the de-mapper, in a hard-decoding fashion, it can be performed according to the signal of $\Lambda(\mathbf{y})$, where a positive value will correspond to an estimate of the sent bit $\hat{b_k}$ as "1", otherwise as "0". However, as previously mentioned, the burden of this decision is assigned to the decoder, which takes advantage of the information built-in the LLR.

For a Gaussian channel the conditional probability can be generally formulated as:

$$p(\mathbf{y}|b_k) = \sum_{s \in \mathbb{S}} \frac{1}{2\pi\sigma^2} e^{-\frac{(\mathbf{y}-s)^2}{2\sigma^2}}, \quad k \in [0, 1, \ldots, \log_2(M) - 1] \text{ and } b_k \in [0, 1] \tag{E.4}$$

It should be noted however that bits $[b_0, b_1, ..., b_k]$ are Gray coded representations of the different symbols of a specific M-QAM constellation. Particularly the used Gray encoding is based on a separated orthogonal representation where the first $\frac{\log_2 M}{2}$ represent the in-phase components while the remainder represent the quadrature components of each symbol. This means that the soft-bit calculation can be performed in parallel, where the same LLR calculation mechanism can be used in parallel and similarly to both components.

The LLR representation also includes the level of certainty, which can be derived from its absolute value, when decision is to be taken. This means that if a value is larger in magnitude there is a greater certainty in the decision process. Conversely, a value close to zero means that more uncertainty is present when deciding about the symbol that was sent. The magnitude of the LLR is used by recursive decoders to regenerate incorrectly received bits, up to a certain point.

The determination of the LLR may involve the calculation of several sums of exponential terms, which can be morose and increasingly complex according to the modulation index. Moreover the LLR definition corresponds to what is often known as log-sum-exp formulation from which underflow issues are known to occur. This problem can be tackled in two ways, either by approximating the expression or by using a log-sum-exp formula, often called the "log-sum-exp trick".

In the first approach the LLR expression can be approximated either by considering the dominant terms of the exponential terms or by approximating the log-sum-exp, as suggested in [148] by using Eq. E.5, where $[a_0, \cdots, a_k]$ are the $k$ exponential terms of Eq. E.4.

$$\max\{a_1, a_2, \ldots, a_k\} \leq \log(e^{a_1} + e^{a_2} + \ldots + e^{a_k}) \leq \max\{a_1, a_2, \ldots, a_k\} + \log k \tag{E.5}$$

The second approach involves the manipulation of log-sum-exp according to the Eq.E.6, where the $y_{max}$ component is responsible for shifting the exponential components nearer to the origin thus reducing the overall underflow phenomena by limiting the number of affected exponential components [147].

$$\log \sum_k e^{a_k} = a_{\max} + \log \sum_k e^{(a_k - a_{\max})}, \quad \text{where } a_{\max} = \max(a_k), \quad \forall_k \tag{E.6}$$

The following section addresses the calculation of the LLR using the complete formulation and the approximations. In the complete formulation the log-num-exp formulation was considered whereas in the approximations a linearization of the exponential sums by intervals, according to the characteristics of the constellations used in IEEE 1901, based on the methodology suggested in [149]. For simplicity, only the LRR for in-phase bits will be considered in order to illustrate the LLR calculation since the same reasoning is applicable to the remainder quadrature bits. For the illustration purpose the signal constellations are considered to be de-normalized.

## E.1 16-QAM

This constellation is mapped through 4 bits $[b_0, b_1, b_2, b_3]$ and in Fig. E.1 illustrates the decision regions pertaining to the in-phase bits $b_0$ on the left and $b_1$ on the right.

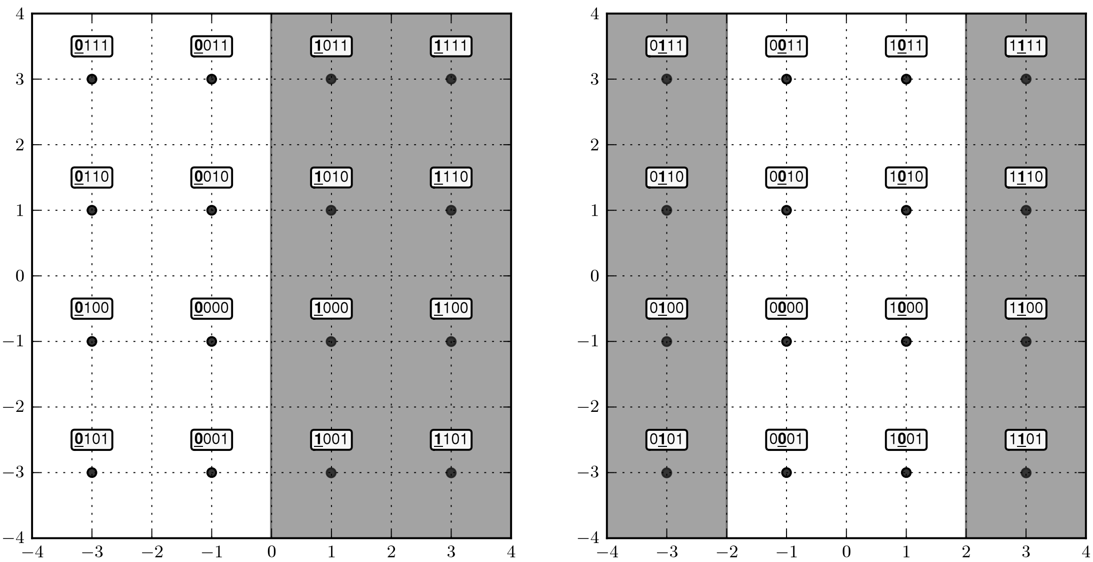


Figure E.1: 16-QAM Decision Regions

For bit $b_0$:

$$P(y|b_0 = 1) = \frac{1}{2\pi\sigma^2}\left[e^{-\frac{(y-1)^2}{2\sigma^2}} + e^{-\frac{(y-3)^2}{2\sigma^2}}\right] \tag{E.7a}$$

$$P(y|b_0 = 0) = \frac{1}{2\pi\sigma^2}\left[e^{-\frac{(y+1)^2}{2\sigma^2}} + e^{-\frac{(y+3)^2}{2\sigma^2}}\right] \tag{E.7b}$$

The log-likelihood ratio (LLR) of bit $b_0$:

$$\Lambda_{b_0} = \log \frac{e^{-\frac{(y-1)^2}{2\sigma^2}} + e^{-\frac{(y-3)^2}{2\sigma^2}}}{e^{-\frac{(y+1)^2}{2\sigma^2}} + e^{-\frac{(y+3)^2}{2\sigma^2}}} \tag{E.8}$$

A linearization of the LLR function can be derived for the following segments considering the dominant exponential terms.

$$\Lambda_{b_0} \approx \begin{cases} -\frac{(y-1)^2}{2\sigma^2} + \frac{(y+3)^2}{2\sigma^2} = \frac{4}{\sigma^2}(y+1), & y \leq -2 \\ -\frac{(y-1)^2}{2\sigma^2} + \frac{(y+1)^2}{2\sigma^2} = \frac{2}{\sigma^2}(y), & -2 < y \leq 2 \\ -\frac{(y-3)^2}{2\sigma^2} + \frac{(y+1)^2}{2\sigma^2} = \frac{4}{\sigma^2}(y-1), & y > 2 \end{cases} \tag{E.9}$$

<u>For bit $b_1$:</u>

$$P(y|b_1 = 1) = \frac{1}{2\pi\sigma^2}\left[e^{-\frac{(y+1)^2}{2\sigma^2}} + e^{-\frac{(y-1)^2}{2\sigma^2}}\right] \tag{E.10a}$$

$$P(y|b_1 = 0) = \frac{1}{2\pi\sigma^2}\left[e^{-\frac{(y+3)^2}{2\sigma^2}} + e^{-\frac{(y-3)^2}{2\sigma^2}}\right] \tag{E.10b}$$

The log-likelihood ratio (LLR) of bit $b_1$:

$$\Lambda_{b_1} = \log \frac{e^{-\frac{(y+1)^2}{2\sigma^2}} + e^{-\frac{(y-1)^2}{2\sigma^2}}}{e^{-\frac{(y+3)^2}{2\sigma^2}} + e^{-\frac{(y-3)^2}{2\sigma^2}}} \tag{E.11}$$

A linearization of the LLR function can be derived for the following segments considering the dominant exponential terms.

$$\Lambda_{b_1} \approx \begin{cases} -\frac{(y+1)^2}{2\sigma^2} + \frac{(y+3)^2}{2\sigma^2} = \frac{2}{\sigma^2}(y+2), & y \leq 0 \\ -\frac{(y-1)^2}{2\sigma^2} + \frac{(y-3)^2}{2\sigma^2} = \frac{2}{\sigma^2}(2-y), & y > 0 \end{cases} \tag{E.12}$$

## E.2 64-QAM

This constellation is mapped through 6 bits $[b_0, b_1, b_2, b_3, b_4, b_5]$ and Fig. E.2 illustrates the decision regions concerning the in-phase bits $b_0$ on the top left, $b_1$ on the top right and $b_2$ at the bottom.

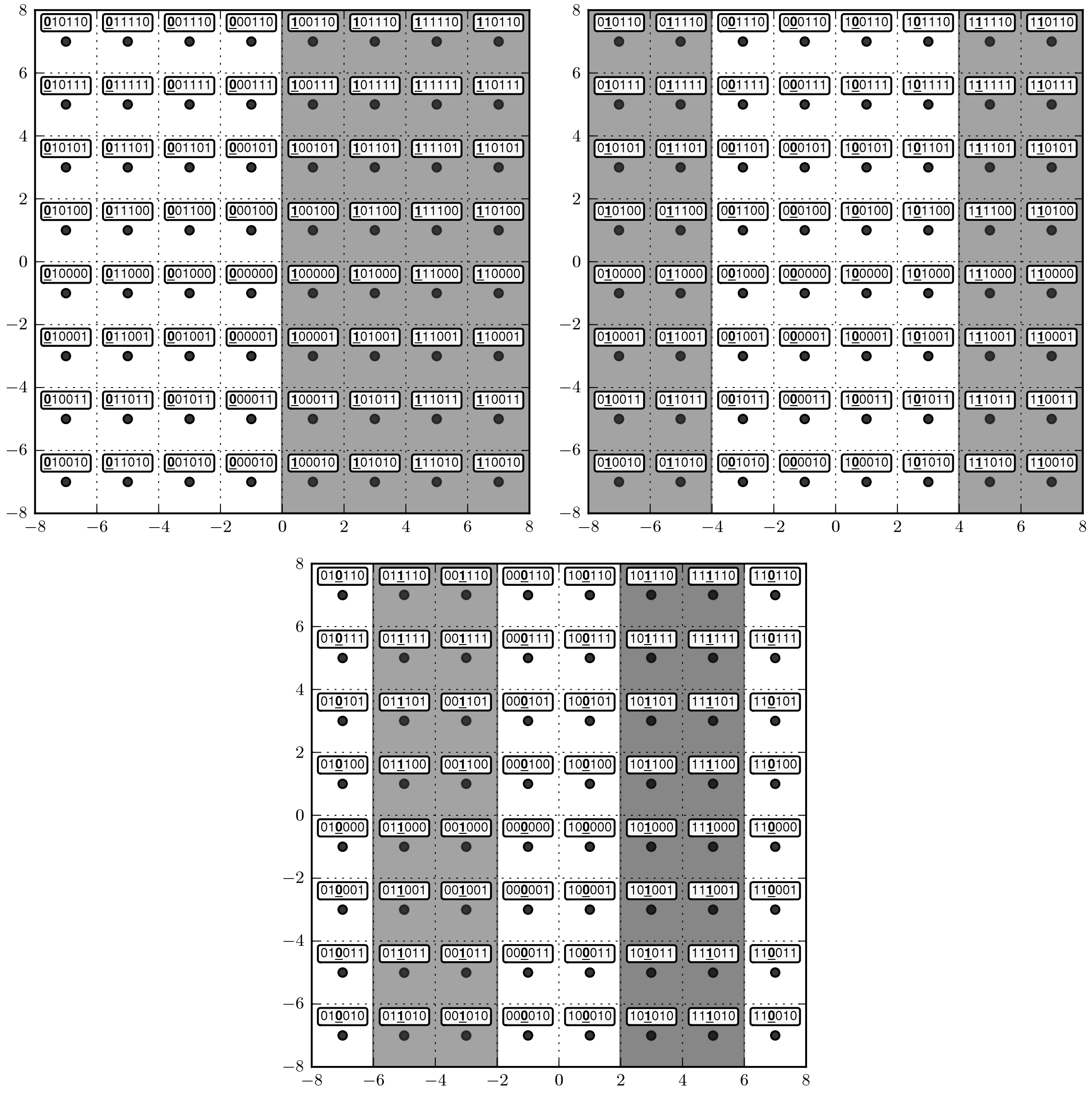


Figure E.2: 64-QAM Decision Regions

For bit $b_0$:

$$P(y|b_0 = 1) = \frac{1}{2\pi\sigma^2}\left[e^{-\frac{(y-1)^2}{2\sigma^2}} + e^{-\frac{(y-3)^2}{2\sigma^2}} + e^{-\frac{(y-5)^2}{2\sigma^2}} + e^{-\frac{(y-7)^2}{2\sigma^2}}\right] \tag{E.13a}$$

$$P(y|b_0=0)=\frac{1}{2\pi\sigma^2}\left[e^{-\frac{(y+1)^2}{2\sigma^2}}+e^{-\frac{(y+3)^2}{2\sigma^2}}+e^{-\frac{(y+5)^2}{2\sigma^2}}+e^{-\frac{(y+7)^2}{2\sigma^2}}\right] \tag{E.13b}$$

The log-likelihood ratio (LLR) of bit $b_0$:

$$\Lambda_{b_0}=\log\frac{e^{-\frac{(y-1)^2}{2\sigma^2}}+e^{-\frac{(y-3)^2}{2\sigma^2}}+e^{-\frac{(y-5)^2}{2\sigma^2}}+e^{-\frac{(y-7)^2}{2\sigma^2}}}{e^{-\frac{(y+1)^2}{2\sigma^2}}+e^{-\frac{(y+3)^2}{2\sigma^2}}+e^{-\frac{(y+5)^2}{2\sigma^2}}+e^{-\frac{(y+7)^2}{2\sigma^2}}} \tag{E.14}$$

A linearization of the LLR function can be derived for the following segments considering the dominant exponential terms.

$$\Lambda_{b_0}\approx\begin{cases}-\frac{(y-1)^2}{2\sigma^2}+\frac{(y+7)^2}{2\sigma^2}=\frac{8}{\sigma^2}(y+3), & y\le -6\\ -\frac{(y-1)^2}{2\sigma^2}+\frac{(y+5)^2}{2\sigma^2}=\frac{6}{\sigma^2}(y+2), & -6<y\le -4\\ -\frac{(y-1)^2}{2\sigma^2}+\frac{(y+3)^2}{2\sigma^2}=\frac{4}{\sigma^2}(y+1), & -4<y\le -2\\ -\frac{(y-1)^2}{2\sigma^2}+\frac{(y+1)^2}{2\sigma^2}=\frac{2}{\sigma^2}(y), & -2<y\le 2\\ -\frac{(y-3)^2}{2\sigma^2}+\frac{(y+1)^2}{2\sigma^2}=\frac{4}{\sigma^2}(y-1), & 2<y\le 4\\ -\frac{(y-5)^2}{2\sigma^2}+\frac{(y+1)^2}{2\sigma^2}=\frac{6}{\sigma^2}(y-2), & 4<y\le 6\\ -\frac{(y-7)^2}{2\sigma^2}+\frac{(y+1)^2}{2\sigma^2}=\frac{8}{\sigma^2}(y-3), & y>6\end{cases} \tag{E.15}$$

For bit $b_1$:

$$P(y|b_1=1)=\frac{1}{2\pi\sigma^2}\left[e^{-\frac{(y-5)^2}{2\sigma^2}}+e^{-\frac{(y-7)^2}{2\sigma^2}}+e^{-\frac{(y+5)^2}{2\sigma^2}}+e^{-\frac{(y+7)^2}{2\sigma^2}}\right] \tag{E.16a}$$

$$P(y|b_1=0)=\frac{1}{2\pi\sigma^2}\left[e^{-\frac{(y-1)^2}{2\sigma^2}}+e^{-\frac{(y-3)^2}{2\sigma^2}}+e^{-\frac{(y+1)^2}{2\sigma^2}}+e^{-\frac{(y+3)^2}{2\sigma^2}}\right] \tag{E.16b}$$

The log-likelihood ratio (LLR) of bit $b_1$:

$$\Lambda_{b_1}=\log\frac{e^{-\frac{(y-5)^2}{2\sigma^2}}+e^{-\frac{(y-7)^2}{2\sigma^2}}+e^{-\frac{(y+5)^2}{2\sigma^2}}+e^{-\frac{(y+7)^2}{2\sigma^2}}}{e^{-\frac{(y-1)^2}{2\sigma^2}}+e^{-\frac{(y-3)^2}{2\sigma^2}}+e^{-\frac{(y+1)^2}{2\sigma^2}}+e^{-\frac{(y+3)^2}{2\sigma^2}}} \tag{E.17}$$

A linearization of the LLR function can be derived for the following segments considering the dominant exponential terms.

$$\Lambda_{b_0}\approx\begin{cases}-\frac{(y-7)^2}{2\sigma^2}+\frac{(y+3)^2}{2\sigma^2}=\frac{10}{\sigma^2}(y-2), & y\le -6\\ -\frac{(y+5)^2}{2\sigma^2}+\frac{(y+3)^2}{2\sigma^2}=\frac{8}{\sigma^2}(y-1), & -6<y\le -2\\ -\frac{(y+5)^2}{2\sigma^2}+\frac{(y+1)^2}{2\sigma^2}=\frac{6}{\sigma^2}(y-2), & -2<y\le 0\\ -\frac{(y-5)^2}{2\sigma^2}+\frac{(y-1)^2}{2\sigma^2}=\frac{4}{\sigma^2}(y-3), & 0<y\le 2\\ -\frac{(y-5)^2}{2\sigma^2}+\frac{(y-3)^2}{2\sigma^2}=\frac{2}{\sigma^2}(y-4), & 2<y\le 6\\ -\frac{(y-7)^2}{2\sigma^2}+\frac{(y-3)^2}{2\sigma^2}=\frac{4}{\sigma^2}(y-5), & y>6\end{cases} \tag{E.18}$$

For bit $b_2$:

$$P(y|b_2=1)=\frac{1}{2\pi\sigma^2}\left[e^{-\frac{(y-3)^2}{2\sigma^2}}+e^{-\frac{(y-5)^2}{2\sigma^2}}+e^{-\frac{(y+3)^2}{2\sigma^2}}+e^{-\frac{(y+5)^2}{2\sigma^2}}\right] \tag{E.19a}$$

$$P(y|b_2=0)=\frac{1}{2\pi\sigma^2}\left[e^{-\frac{(y-1)^2}{2\sigma^2}}+e^{-\frac{(y-7)^2}{2\sigma^2}}+e^{-\frac{(y+1)^2}{2\sigma^2}}+e^{-\frac{(y+7)^2}{2\sigma^2}}\right] \tag{E.19b}$$

The log-likelihood ratio (LLR) of bit $b_1$:

$$\Lambda_{b_2}=\log\frac{e^{-\frac{(y-3)^2}{2\sigma^2}}+e^{-\frac{(y-5)^2}{2\sigma^2}}+e^{-\frac{(y+3)^2}{2\sigma^2}}+e^{-\frac{(y+5)^2}{2\sigma^2}}}{e^{-\frac{(y-1)^2}{2\sigma^2}}+e^{-\frac{(y-7)^2}{2\sigma^2}}+e^{-\frac{(y+1)^2}{2\sigma^2}}+e^{-\frac{(y+7)^2}{2\sigma^2}}} \tag{E.20}$$

A linearization of the LLR function can be derived for the following segments considering the dominant exponential terms.

If $y\leq -4$:

$$\Lambda_{b_2}\approx-\frac{(y+5)^2}{2\sigma^2}+\frac{(y+7)^2}{2\sigma^2}=\frac{2}{\sigma^2}(y+1) \tag{E.21}$$

$$\Lambda_{b_2}\approx\begin{cases}-\frac{(y+5)^2}{2\sigma^2}+\frac{(y+7)^2}{2\sigma^2}=\frac{2}{\sigma^2}(y+1), & y\leq -4\\ -\frac{(y+3)^2}{2\sigma^2}+\frac{(y+1)^2}{2\sigma^2}=\frac{2}{\sigma^2}(-y-2), & -4<y\leq 0\\ -\frac{(y-3)^2}{2\sigma^2}+\frac{(y-1)^2}{2\sigma^2}=\frac{2}{\sigma^2}(y-2), & 0<y\leq 4\\ -\frac{(y-5)^2}{2\sigma^2}+\frac{(y-7)^2}{2\sigma^2}=\frac{2}{\sigma^2}(-y+2), & y>4\end{cases} \tag{E.22}$$

## E.3 256-QAM

This constellation is mapped through 8 bits $[b_0,b_1,b_2,b_3,b_4,b_5,b_6,b_7]$. This constellation is not depicted since it is impractical to represent its dense mapping and associated regions of decision.

For bit $b_0$:

$$P(y|b_0=1)=\frac{1}{2\pi\sigma^2}\left[e^{-\frac{(y-1)^2}{2\sigma^2}}+e^{-\frac{(y-3)^2}{2\sigma^2}}+e^{-\frac{(y-5)^2}{2\sigma^2}}+e^{-\frac{(y-7)^2}{2\sigma^2}}e^{-\frac{(y-9)^2}{2\sigma^2}}+e^{-\frac{(y-11)^2}{2\sigma^2}}+e^{-\frac{(y-13)^2}{2\sigma^2}}+e^{-\frac{(y-15)^2}{2\sigma^2}}\right] \tag{E.23a}$$

$$P(y|b_0=0)=\frac{1}{2\pi\sigma^2}\left[e^{-\frac{(y+1)^2}{2\sigma^2}}+e^{-\frac{(y+3)^2}{2\sigma^2}}+e^{-\frac{(y+5)^2}{2\sigma^2}}+e^{-\frac{(y+7)^2}{2\sigma^2}}e^{-\frac{(y+9)^2}{2\sigma^2}}+e^{-\frac{(y+11)^2}{2\sigma^2}}+e^{-\frac{(y+13)^2}{2\sigma^2}}+e^{-\frac{(y+15)^2}{2\sigma^2}}\right] \tag{E.23b}$$

The log-likelihood ratio (LLR) of bit $b_0$:

$$\Lambda_{b_0}=\log\frac{e^{-\frac{(y-1)^2}{2\sigma^2}}+e^{-\frac{(y-3)^2}{2\sigma^2}}+e^{-\frac{(y-5)^2}{2\sigma^2}}+e^{-\frac{(y-7)^2}{2\sigma^2}}+e^{-\frac{(y-9)^2}{2\sigma^2}}+e^{-\frac{(y-11)^2}{2\sigma^2}}+e^{-\frac{(y-13)^2}{2\sigma^2}}+e^{-\frac{(y-15)^2}{2\sigma^2}}}{e^{-\frac{(y+1)^2}{2\sigma^2}}+e^{-\frac{(y+3)^2}{2\sigma^2}}+e^{-\frac{(y+5)^2}{2\sigma^2}}+e^{-\frac{(y+7)^2}{2\sigma^2}}+e^{-\frac{(y+9)^2}{2\sigma^2}}+e^{-\frac{(y+11)^2}{2\sigma^2}}+e^{-\frac{(y+13)^2}{2\sigma^2}}+e^{-\frac{(y+15)^2}{2\sigma^2}}} \tag{E.24}$$

A linearization of the LLR function can be derived for the following segments considering the dominant exponential terms.

$$\Lambda_{b_0} \approx \begin{cases} -\frac{(y-1)^2}{2\sigma^2} + \frac{(y+15)^2}{2\sigma^2} = \frac{16}{\sigma^2}(y+7), & y \le -14 \\ -\frac{(y-1)^2}{2\sigma^2} + \frac{(y+13)^2}{2\sigma^2} = \frac{14}{\sigma^2}(y+6), & -14 < y \le -12 \\ -\frac{(y-1)^2}{2\sigma^2} + \frac{(y+11)^2}{2\sigma^2} = \frac{12}{\sigma^2}(y+5), & -12 < y \le -10 \\ -\frac{(y-1)^2}{2\sigma^2} + \frac{(y+9)^2}{2\sigma^2} = \frac{10}{\sigma^2}(y+4), & -10 < y \le -8 \\ -\frac{(y-1)^2}{2\sigma^2} + \frac{(y+7)^2}{2\sigma^2} = \frac{8}{\sigma^2}(y+3), & -8 < y \le -6 \\ -\frac{(y-1)^2}{2\sigma^2} + \frac{(y+5)^2}{2\sigma^2} = \frac{6}{\sigma^2}(y+2), & -6 < y \le -4 \\ -\frac{(y-1)^2}{2\sigma^2} + \frac{(y+3)^2}{2\sigma^2} = \frac{4}{\sigma^2}(y+1), & -4 < y \le -2 \\ -\frac{(y-1)^2}{2\sigma^2} + \frac{(y+1)^2}{2\sigma^2} = \frac{2}{\sigma^2}(y), & -2 < y \le 2 \\ -\frac{(y-3)^2}{2\sigma^2} + \frac{(y+1)^2}{2\sigma^2} = \frac{4}{\sigma^2}(y-1), & 2 < y \le 4 \\ -\frac{(y-5)^2}{2\sigma^2} + \frac{(y+1)^2}{2\sigma^2} = \frac{6}{\sigma^2}(y-2), & 4 < y \le 6 \\ -\frac{(y-7)^2}{2\sigma^2} + \frac{(y+1)^2}{2\sigma^2} = \frac{8}{\sigma^2}(y-3), & 6 < y \le 8 \\ -\frac{(y-9)^2}{2\sigma^2} + \frac{(y+1)^2}{2\sigma^2} = \frac{10}{\sigma^2}(y-4), & 8 < y \le 10 \\ -\frac{(y-11)^2}{2\sigma^2} + \frac{(y+1)^2}{2\sigma^2} = \frac{12}{\sigma^2}(y-5), & 10 < y \le 12 \\ -\frac{(y-13)^2}{2\sigma^2} + \frac{(y+1)^2}{2\sigma^2} = \frac{14}{\sigma^2}(y-6), & 12 < y \le 14 \\ -\frac{(y-15)^2}{2\sigma^2} + \frac{(y+1)^2}{2\sigma^2} = \frac{16}{\sigma^2}(y-7), & y > 14 \end{cases} \tag{E.25}$$

For bit $b_1$:

$$P(y|b_1=1) = \frac{1}{2\pi\sigma^2}\left[e^{-\frac{(y-9)^2}{2\sigma^2}} + e^{-\frac{(y-11)^2}{2\sigma^2}} + e^{-\frac{(y-13)^2}{2\sigma^2}} + e^{-\frac{(y-15)^2}{2\sigma^2}} e^{-\frac{(y+9)^2}{2\sigma^2}} + e^{-\frac{(y+11)^2}{2\sigma^2}} + e^{-\frac{(y+13)^2}{2\sigma^2}} + e^{-\frac{(y+15)^2}{2\sigma^2}}\right] \tag{E.26a}$$

$$P(y|b_1=0) = \frac{1}{2\pi\sigma^2}\left[e^{-\frac{(y-1)^2}{2\sigma^2}} + e^{-\frac{(y-3)^2}{2\sigma^2}} + e^{-\frac{(y-5)^2}{2\sigma^2}} + e^{-\frac{(y-7)^2}{2\sigma^2}} e^{-\frac{(y+11)^2}{2\sigma^2}} + e^{-\frac{(y+13)^2}{2\sigma^2}} + e^{-\frac{(y+15)^2}{2\sigma^2}} + e^{-\frac{(y+17)^2}{2\sigma^2}}\right] \tag{E.26b}$$

The log-likelihood ratio (LLR) of bit $b_1$:

$$\Lambda_{b_1} = \log \frac{e^{-\frac{(y-1)^2}{2\sigma^2}} + e^{-\frac{(y-3)^2}{2\sigma^2}} + e^{-\frac{(y-5)^2}{2\sigma^2}} + e^{-\frac{(y-7)^2}{2\sigma^2}} + e^{-\frac{(y-9)^2}{2\sigma^2}} + e^{-\frac{(y-11)^2}{2\sigma^2}} + e^{-\frac{(y-13)^2}{2\sigma^2}} + e^{-\frac{(y-15)^2}{2\sigma^2}}}{e^{-\frac{(y+1)^2}{2\sigma^2}} + e^{-\frac{(y+3)^2}{2\sigma^2}} + e^{-\frac{(y+5)^2}{2\sigma^2}} + e^{-\frac{(y+7)^2}{2\sigma^2}} + e^{-\frac{(y+9)^2}{2\sigma^2}} + e^{-\frac{(y+11)^2}{2\sigma^2}} + e^{-\frac{(y+13)^2}{2\sigma^2}} + e^{-\frac{(y+15)^2}{2\sigma^2}}} \tag{E.27}$$

A linearization of the LLR function can be derived for the following segments considering the dominant exponential terms.

$$\Lambda_{b_1} \approx \begin{cases} -\frac{(y+15)^2}{2\sigma^2} + \frac{(y+7)^2}{2\sigma^2} = \frac{8}{\sigma^2}(-y-11), & y \le -14 \\ -\frac{(y+13)^2}{2\sigma^2} + \frac{(y+7)^2}{2\sigma^2} = \frac{6}{\sigma^2}(-y-10), & -14 < y \le -12 \\ -\frac{(y+11)^2}{2\sigma^2} + \frac{(y+7)^2}{2\sigma^2} = \frac{4}{\sigma^2}(-y-9), & -12 < y \le -10 \\ -\frac{(y+9)^2}{2\sigma^2} + \frac{(y+7)^2}{2\sigma^2} = \frac{2}{\sigma^2}(-y-8), & -10 < y \le -6 \\ -\frac{(y+9)^2}{2\sigma^2} + \frac{(y+5)^2}{2\sigma^2} = \frac{4}{\sigma^2}(-y-7), & -6 < y \le -4 \\ -\frac{(y+9)^2}{2\sigma^2} + \frac{(y+3)^2}{2\sigma^2} = \frac{6}{\sigma^2}(-y-6), & -4 < y \le -2 \\ -\frac{(y+9)^2}{2\sigma^2} + \frac{(y+1)^2}{2\sigma^2} = \frac{8}{\sigma^2}(-y-5), & -2 < y \le 0 \\ -\frac{(y-9)^2}{2\sigma^2} + \frac{(y-1)^2}{2\sigma^2} = \frac{8}{\sigma^2}(y-5), & 0 < y \le 2 \\ -\frac{(y-9)^2}{2\sigma^2} + \frac{(y-3)^2}{2\sigma^2} = \frac{6}{\sigma^2}(y-6), & 2 < y \le 4 \\ -\frac{(y-9)^2}{2\sigma^2} + \frac{(y-5)^2}{2\sigma^2} = \frac{4}{\sigma^2}(y-7), & 4 < y \le 6 \\ -\frac{(y-9)^2}{2\sigma^2} + \frac{(y-7)^2}{2\sigma^2} = \frac{2}{\sigma^2}(y-8), & 6 < y \le 10 \\ -\frac{(y-11)^2}{2\sigma^2} + \frac{(y-7)^2}{2\sigma^2} = \frac{4}{\sigma^2}(y-9), & 10 < y \le 12 \\ -\frac{(y-13)^2}{2\sigma^2} + \frac{(y-7)^2}{2\sigma^2} = \frac{6}{\sigma^2}(y-10), & 12 < y \le 14 \\ -\frac{(y-15)^2}{2\sigma^2} + \frac{(y-7)^2}{2\sigma^2} = \frac{8}{\sigma^2}(y-11), & y > 14 \end{cases} \tag{E.28}$$

For bit $b_2$:

$$P(y|b_2=1) = \frac{1}{2\pi\sigma^2}\left[e^{-\frac{(y-5)^2}{2\sigma^2}} + e^{-\frac{(y-7)^2}{2\sigma^2}} + e^{-\frac{(y-9)^2}{2\sigma^2}} + e^{-\frac{(y-11)^2}{2\sigma^2}} + e^{-\frac{(y+5)^2}{2\sigma^2}} + e^{-\frac{(y+7)^2}{2\sigma^2}} + e^{-\frac{(y+9)^2}{2\sigma^2}} + e^{-\frac{(y+11)^2}{2\sigma^2}}\right] \tag{E.29a}$$

$$P(y|b_2=0) = \frac{1}{2\pi\sigma^2}\left[e^{-\frac{(y-1)^2}{2\sigma^2}} + e^{-\frac{(y-3)^2}{2\sigma^2}} + e^{-\frac{(y-13)^2}{2\sigma^2}} + e^{-\frac{(y-15)^2}{2\sigma^2}} + e^{-\frac{(y+1)^2}{2\sigma^2}} + e^{-\frac{(y+3)^2}{2\sigma^2}} + e^{-\frac{(y+13)^2}{2\sigma^2}} + e^{-\frac{(y+15)^2}{2\sigma^2}}\right] \tag{E.29b}$$

The log-likelihood ratio (LLR) of bit $b_2$:

$$\Lambda_{b_2} = \log \frac{e^{-\frac{(y-5)^2}{2\sigma^2}} + e^{-\frac{(y-7)^2}{2\sigma^2}} + e^{-\frac{(y-9)^2}{2\sigma^2}} + e^{-\frac{(y-11)^2}{2\sigma^2}} + e^{-\frac{(y+5)^2}{2\sigma^2}} + e^{-\frac{(y+7)^2}{2\sigma^2}} + e^{-\frac{(y+9)^2}{2\sigma^2}} + e^{-\frac{(y+11)^2}{2\sigma^2}}}{e^{-\frac{(y+1)^2}{2\sigma^2}} + e^{-\frac{(y+3)^2}{2\sigma^2}} + e^{-\frac{(y+5)^2}{2\sigma^2}} + e^{-\frac{(y+7)^2}{2\sigma^2}} + e^{-\frac{(y+9)^2}{2\sigma^2}} + e^{-\frac{(y+11)^2}{2\sigma^2}} + e^{-\frac{(y+13)^2}{2\sigma^2}} + e^{-\frac{(y+15)^2}{2\sigma^2}}} \tag{E.30}$$

A linearization of the LLR function can be derived for the following segments considering the dominant exponential terms.

$$\Lambda_{b_2} \approx \begin{cases} -\frac{(y+11)^2}{2\sigma^2} + \frac{(y+15)^2}{2\sigma^2} = \frac{4}{\sigma^2}(y+13), & y \leq -14 \\ -\frac{(y+11)^2}{2\sigma^2} + \frac{(y+13)^2}{2\sigma^2} = \frac{2}{\sigma^2}(y+12), & -14 < y \leq -12 \\ -\frac{(y+9)^2}{2\sigma^2} + \frac{(y+13)^2}{2\sigma^2} = \frac{4}{\sigma^2}(y+11), & -12 < y \leq -10 \\ -\frac{(y+7)^2}{2\sigma^2} + \frac{(y+3)^2}{2\sigma^2} = \frac{4}{\sigma^2}(-y-5), & -10 < y \leq -6 \\ -\frac{(y+5)^2}{2\sigma^2} + \frac{(y+3)^2}{2\sigma^2} = \frac{2}{\sigma^2}(-y-4), & -6 < y \leq -2 \\ -\frac{(y+5)^2}{2\sigma^2} + \frac{(y+1)^2}{2\sigma^2} = \frac{4}{\sigma^2}(-y-3), & -2 < y \leq 0 \\ -\frac{(y-9)^2}{2\sigma^2} + \frac{(y-1)^2}{2\sigma^2} = \frac{4}{\sigma^2}(y-3), & 0 < y \leq 2 \\ -\frac{(y-9)^2}{2\sigma^2} + \frac{(y-5)^2}{2\sigma^2} = \frac{2}{\sigma^2}(y-4), & 2 < y \leq 6 \\ -\frac{(y-9)^2}{2\sigma^2} + \frac{(y-7)^2}{2\sigma^2} = \frac{4}{\sigma^2}(y-5), & 6 < y \leq 10 \\ -\frac{(y-11)^2}{2\sigma^2} + \frac{(y-7)^2}{2\sigma^2} = \frac{4}{\sigma^2}(y-11), & 10 < y \leq 12 \\ -\frac{(y-13)^2}{2\sigma^2} + \frac{(y-7)^2}{2\sigma^2} = \frac{2}{\sigma^2}(y-12), & 12 < y \leq 14 \\ -\frac{(y-15)^2}{2\sigma^2} + \frac{(y-7)^2}{2\sigma^2} = \frac{4}{\sigma^2}(y-13), & y > 14 \end{cases} \tag{E.31}$$

<u>For bit $b_3$:</u>

$$P(y|b_3=1) = \frac{1}{2\pi\sigma^2}\left[e^{-\frac{(y-3)^2}{2\sigma^2}} + e^{-\frac{(y-5)^2}{2\sigma^2}} + e^{-\frac{(y-11)^2}{2\sigma^2}} + e^{-\frac{(y-13)^2}{2\sigma^2}} + e^{-\frac{(y+3)^2}{2\sigma^2}} + e^{-\frac{(y+5)^2}{2\sigma^2}} + e^{-\frac{(y+11)^2}{2\sigma^2}} + e^{-\frac{(y+13)^2}{2\sigma^2}}\right] \tag{E.32a}$$

$$P(y|b_3=0) = \frac{1}{2\pi\sigma^2}\left[e^{-\frac{(y-1)^2}{2\sigma^2}} + e^{-\frac{(y-7)^2}{2\sigma^2}} + e^{-\frac{(y-9)^2}{2\sigma^2}} + e^{-\frac{(y-15)^2}{2\sigma^2}} + e^{-\frac{(y+1)^2}{2\sigma^2}} + e^{-\frac{(y+7)^2}{2\sigma^2}} + e^{-\frac{(y+9)^2}{2\sigma^2}} + e^{-\frac{(y+15)^2}{2\sigma^2}}\right] \tag{E.32b}$$

The log-likelihood ratio (LLR) of bit $b_2$:

$$\Lambda_{b_3} = \log \frac{e^{-\frac{(y-3)^2}{2\sigma^2}} + e^{-\frac{(y-5)^2}{2\sigma^2}} + e^{-\frac{(y-11)^2}{2\sigma^2}} + e^{-\frac{(y-13)^2}{2\sigma^2}} + e^{-\frac{(y+3)^2}{2\sigma^2}} + e^{-\frac{(y+5)^2}{2\sigma^2}} + e^{-\frac{(y+11)^2}{2\sigma^2}} + e^{-\frac{(y+13)^2}{2\sigma^2}}}{e^{-\frac{(y-1)^2}{2\sigma^2}} + e^{-\frac{(y-7)^2}{2\sigma^2}} + e^{-\frac{(y-9)^2}{2\sigma^2}} + e^{-\frac{(y-15)^2}{2\sigma^2}} + e^{-\frac{(y+1)^2}{2\sigma^2}} + e^{-\frac{(y+7)^2}{2\sigma^2}} + e^{-\frac{(y+9)^2}{2\sigma^2}} + e^{-\frac{(y+15)^2}{2\sigma^2}}} \tag{E.33}$$

A linearization of the LLR function can be derived for the following segments considering the dominant exponential terms.

$$\Lambda_{b_3} \approx \begin{cases} -\frac{(y+13)^2}{2\sigma^2} + \frac{(y+15)^2}{2\sigma^2} = \frac{2}{\sigma^2}(y+14), & y \leq -12 \\ -\frac{(y+11)^2}{2\sigma^2} + \frac{(y+9)^2}{2\sigma^2} = \frac{2}{\sigma^2}(-y-10), & -12 < y \leq -8 \\ -\frac{(y+5)^2}{2\sigma^2} + \frac{(y+7)^2}{2\sigma^2} = \frac{2}{\sigma^2}(y+6), & -8 < y \leq -4 \\ -\frac{(y+3)^2}{2\sigma^2} + \frac{(y+1)^2}{2\sigma^2} = \frac{2}{\sigma^2}(-y-2), & -4 < y \leq 0 \\ -\frac{(y-3)^2}{2\sigma^2} + \frac{(y-1)^2}{2\sigma^2} = \frac{2}{\sigma^2}(y-2), & 0 < y \leq 4 \\ -\frac{(y-5)^2}{2\sigma^2} + \frac{(y-7)^2}{2\sigma^2} = \frac{2}{\sigma^2}(-y+6), & 4 < y \leq 8 \\ -\frac{(y-11)^2}{2\sigma^2} + \frac{(y-9)^2}{2\sigma^2} = \frac{2}{\sigma^2}(y-10), & 8 < y \leq 12 \\ -\frac{(y-13)^2}{2\sigma^2} + \frac{(y-15)^2}{2\sigma^2} = \frac{2}{\sigma^2}(-y+14), & y > 12 \end{cases} \tag{E.34}$$

# Appendix F

# Double-Binary Turbo Decoding

This appendix addresses the turbo decoding basics and the respective mathematical formulation used in each of the decoder blocks presented in Section 4.5.1. As illustrated in Fig. 4.14, the decoding architecture will produce an estimate of the initial sent sequence. This Appendix does not discuss the fundamentals of the decoding algorithm itself, which can be consulted from the original work presented by Berrou and Glavieux in [150], but rather the calculation of metrics adapted for the double-binary case defined according to the IEEE1901 standard. Some generalizations of non-binary encoding are also presented.

The notation used in the present formulation is adapted from [151] and uses $u_i$, $x_i$ and $y_i$ for the binary representation of $\boldsymbol{u}_i$=$[u_{i_1} u_{i_2} \cdots u_{i_k}]$, $\boldsymbol{x}_i = [x_{i_1} x_{i_2} \cdots x_{i_n}]$ and $\boldsymbol{y}_i = [y_{i_1} y_{i_2} \cdots y_{i_n}]$ for non-binary symbol representation.

In a binary turbo decoding system during a finite number of iterations the serial decoders will exchange an output metric, which is called extrinsic information, since it only depends on the parity bits used in the encoded sequence $x_i$, to compute more precise values of $\Lambda(u_i|y_i)$. The extrinsic information, $\Lambda_e(u_i)$, is calculated in the form of a LLR and after an interleaving and a deinterleaving process is fed into each of the decoders. After the iterative process the decision receives from the serial decoders an *a posteriori* LLR, $\Lambda(u_i|y_i)$, and based on the signal of each bit estimate it will output a hard decision. Hence in order to implement the iterative decoding process the $\Lambda_e(u_i)$ needs to be computed which is related with $\Lambda(u_i|y)$ through Eq. F.1 as stated in [128]. Its value is related with the decoding fundamentals presented in [150] considering a recursive systematic binary encoding. The basis for this calculation will be revisited later on for the non-binary case.

$$\underbrace{\Lambda(u_i|y_i)}_{a\ posteriori} = \underbrace{\Lambda(u_i)}_{a\ priori} + \underbrace{L_c y_i}_{channel} + \underbrace{\Lambda_e(u_i)}_{extrinsic} \tag{F.1}$$

The decoding algorithm of each decoder is often designated as forward-backward due to its nature, in which a set of internal metrics are calculated within a concatenated trellis structure in a finite iterative process. A thorough description of a single-binary decoding process and algorithm variations can be found in existing literature namely in [151]. In [152] specifics concerning the concatenation and reiteration process are explained in detail.

The decoding process associated with the implemented decoder is based on a non-binary decoding process. In the particular case considered in this Appendix the encoding/decoding system is often referred to as duo-binary or double-binary. This means that the decoding of non-binary sequences or symbols is performed by groups of bits, which in the double-binary case means that pairs of bits or dibits of information, as they are commonly known, are processed together with the respective parity bits. One of the first applications of these particular codes can be found in Digital Video Broadcasting, namely in DVB-RCS standard, where this type of decoding was extensively documented and evaluated. More information on the application of turbo codes in DVB can be found in [153].

The decoding scheme is typically based on the original BCJR algorithm or some of its variants. The goal is the determination of the *a posteriori* LLR value, $\Lambda(u|y)$, to allow the estimation of the sent sequence $u$, given that $y$ was received, and as such the decoding process involves the calculation of intermediate metrics. A graphic representation of the iterative decoding process is often illustrated by means of the concatenation of encoder trellises, as illustrated in Fig. F.1 with as many as $N = k \div 2$, meaning half of the information bits that were originally sent. This conglomerate structure contains every possible transition in the encoder and the objective is to find an end-to-end transition pattern, representing the maximum certainty that the decoder has regarding the sequence that was sent after receiving it through the communications channel. The $S_{i-1} \rightarrow S_i$ transition represents a general case used in the remainder of this appendix, which defined a partition of the decoding process pertaining to the double-binary symbol $\boldsymbol{u}_i$ encoded into $\boldsymbol{x}_i$ and received as $\boldsymbol{y}_i$. The partitioning of $y$ is exemplified in Eq. F.2, where $\boldsymbol{y}_i$ represents a dibit and the respective parity bit, $N$ corresponds, as expected, to half of the information binary sequence.

$$\boldsymbol{y} = \underbrace{\boldsymbol{y}_1\boldsymbol{y}_2\cdots\boldsymbol{y}_{i-1}}_{\boldsymbol{y}_{<i}}\ \boldsymbol{y}_i\ \underbrace{\boldsymbol{y}_{i+1}\cdots\boldsymbol{y}_{N-1}\boldsymbol{y}_N}_{\boldsymbol{y}_{>i}}, \quad \text{where } N = k/2 \tag{F.2}$$

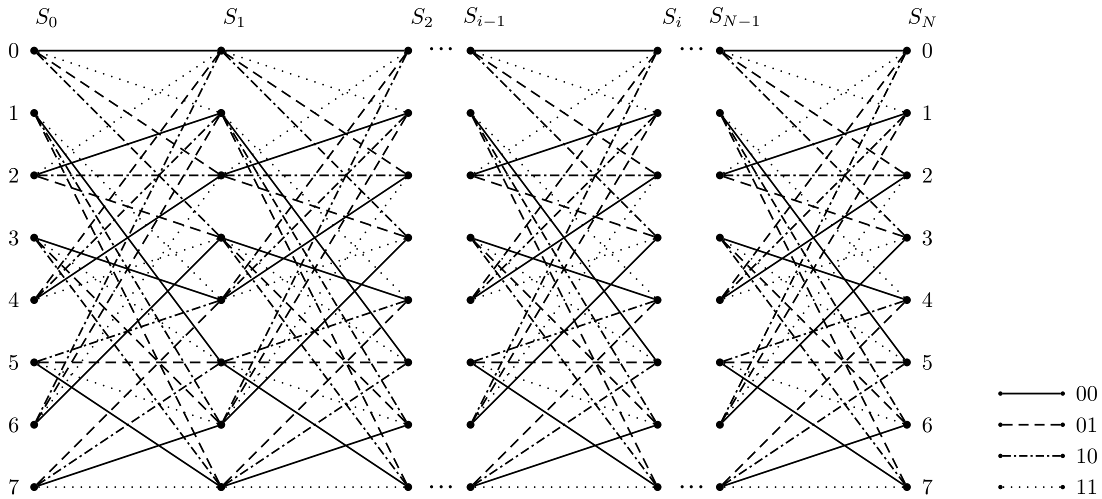


Figure F.1: Concatenated Trellis Decoding

In each decoder the LLR metric is used to evaluate the probability of each dibit and the respective parity bit having been originated by a specific transition between encoder states $S_{i-1}$ and $S_i$. It must be kept in mind the significance of the LLR which, in the binary case, represents the magnitude in the decision preference regarding a single boundary. In non-binary symbol coding the number of boundaries increases with the number of bits used to represent each symbol and, as such, several preferences concerning the inherited boundaries can be established.

As pointed out in [154] the total number of LLRs that is possible to establish in the double-binary codes is 12; nonetheless, it also points out that only three of them will have to be computed for the decoding algorithm to decide about each of the best estimate regarding each pair of bits from the received sequence. This set of LLRs is designated as Multidimensional LLR (MLLR) and can be defined generically according to Eq. F.3, considering the antipodal representation of the binary sequence $\boldsymbol{u}_i$. As expected when $(a,b)$=(-1,-1) the LLR is zero, however for the purpose of a generic formulation this case is included in the MLLR definition.

$$\Lambda_j(\boldsymbol{u}_i|\boldsymbol{y}_i) = \log \frac{P(\boldsymbol{u}_i = (a,b)|\boldsymbol{y}_i)}{P(\boldsymbol{u}_i = (\text{-}1,\text{-}1)|\boldsymbol{y}_i)}, a \in \{\text{-}1,1\} \wedge b \in \{\text{-}1,1\} \wedge j \in \{0,1,2,3\} \tag{F.3}$$

$P(\boldsymbol{u}_i|\boldsymbol{y}_i)$ represents all the probabilities associated with all possible transitions between states where $S_{i-1}$ and $S_i$ triggered by a specific input sequence $\boldsymbol{u}_i$. Hence the LLRs can be generically written as presented in Eq. F.4 where for simplicity the values $(a,b)$ and $j$ are deliberately omitted since they are the same. The $S_{i-1} \rightarrow S_i$ represents a specific state transition, which is triggered by a particular $\boldsymbol{u}_i$ sequence. Each LLR in fact will represent the preference or the certainty of the probability of a sequence $\boldsymbol{u}_i$= (a,b) when compared to $\boldsymbol{u}_i$=(-1,-1). For convenience $P(A \cap B) = P(A,B)$, thus:

$$\Lambda_j(\boldsymbol{u}_i|\boldsymbol{y}_i) = \log \frac{\sum\limits_{\boldsymbol{u}_i=(a,b)} P(S_{i-1} \rightarrow S_i|\boldsymbol{y}_i)}{\sum\limits_{\boldsymbol{u}_i=(\text{-}1,\text{-}1)} P(S_{i-1} \rightarrow S_i|\boldsymbol{y}_i)} = \log \frac{\sum\limits_{\boldsymbol{u}_i=(a,b)} \frac{P((S_{i-1} \rightarrow S_i|y),\boldsymbol{y}_i)}{P(\boldsymbol{y}_i)}}{\sum\limits_{\boldsymbol{u}_i=(\text{-}1,\text{-}1)} \frac{P((S_{i-1} \rightarrow s_i),\boldsymbol{y}_i)}{P(\boldsymbol{y}_i)}} = \log \frac{\sum\limits_{\boldsymbol{u}_i=(a,b)} P((S_{i-1} \rightarrow S_i),y)}{\sum\limits_{\boldsymbol{u}_i=(\text{-}1,\text{-}1)} P((S_{i-1} \rightarrow S_i),y)} \tag{F.4}$$

Due to the absence of memory in the communications channel, the partitions of $\boldsymbol{y}$ can be considered as the output of independent events:

$$P(\boldsymbol{y}) = P(\boldsymbol{y}_{<i})P(\boldsymbol{y}_i)P(\boldsymbol{y}_{>i}) = P(\boldsymbol{y}_{<i}, \boldsymbol{y}_i, \boldsymbol{y}_{>i})$$

The expression $P\left((S_{i-1} \rightarrow S_i|y), y\right)$ can be rewritten for simplicity as $P\left(S_{i-1}, S_i, y\right)$. When considering the partitioning of $y$ the expression then becomes $P\left(S_{i-1}, S_i, y_{<i}, y_i, y_{>i}\right)$. Using the Bayes rule for conditional probability presented in Eq. F.5, then the following algebraic transformations defined in Eq. F.6 can be established, assuming the memoryless nature of the transmission channel:

$$P(A,B) = P(A|B)P(B) \tag{F.5}$$

$$\begin{aligned} p\left(S_{i-1}, S_i, y_{<i}, y_i, y_{>i}\right) &= p(y_{>i}|S_{i-1}, S_i, y_{<i}, y_i)\, p(S_{i-1}, S_i, y_{<i}, y_i) \\ &= p(S_{i-1}, S_i, y_{<i}, y_i\,) p(y_{>i}|S_i) \\ &= p(y_i, S_i|S_{i-1}, y_{<i})\, p(S_{i-1}, y_{<i})\, p(y_{>i}|S_i) \\ &= \underbrace{p(S_{i-1}, y_{<i})}_{\alpha(S_{i-1})}\, \underbrace{p(y_i, S_i|S_{i-1})}_{\gamma(S_{i-1},S_i)}\, \underbrace{p(y_{>i}|S_i)}_{\beta(S_i)} \end{aligned} \tag{F.6}$$

The MLLR defined previously in Eq. F.4 becomes:

$$\Lambda_j(\boldsymbol{u}_i|\boldsymbol{y}_i) = \log \frac{\sum\limits_{\boldsymbol{u}_i=(a,b)} \alpha(S_{i-1})\gamma(S_{i-1},S_i)\beta(S_i)}{\sum\limits_{\boldsymbol{u}_i=(\text{-}1,\text{-}1)} \alpha(S_{i-1})\gamma(S_{i-1},S_i)\beta(S_i)} \tag{F.7}$$

Hence the turbo decoding process consists in calculating the $\alpha(S_{i-1})$, $\gamma(S_{i-1}, S_i)$ and $\beta(S_i)$ functions, defined in Eq.F.7, throughout the concatenated trellises. In fact as it has already been mentioned the decoding algorithm is often called "forward-backward" since it starts by calculating the transitions, $\gamma$, then it goes forward through the trellises to calculate $\alpha$ and backwards to calculate $\beta$ both in a recursive manner.

The calculation of $\gamma(S_{i-1}, S_i)$ for non-binary decoding can be derived from the classic binary decoding strategies, presented for example in [151]. From the binary decoding, it is established that the *a priori* LLR can be defined as:

$$\Lambda(u_i) = \log \frac{P(u_i = 1)}{P(u_i = 0)} = \log \frac{P(u_i = 1)}{1 - P(u_i = 1)} = \log \frac{P(u_i = 0)}{1 - P(u_i = 0)} = \log \frac{P(u_i)}{1 - P(u_i)}, \forall u_i \in \{\text{-}1, 1\}$$

And, as such:

$$P(u_i) = \frac{e^{u_i\Lambda(u_i)}}{1 + e^{u_i\Lambda(u_i)}} = \frac{e^{\frac{\Lambda(u_i)}{2}}}{1 + e^{\Lambda(u_i)}} e^{\frac{u_i\Lambda(u_i)}{2}} = c_i\, e^{\frac{u_i\Lambda(u_i)}{2}}, \forall u_i \in \{\text{-}1, 1\}$$

For the n-binary case and given that the bits in the $\mathbf{u}_i = [u_{i1} \cdots u_{ik}]$ represent independent events the previous expression can be rewritten as:

$$P(\boldsymbol{u}_i) = \prod_{j=1}^{k} P(u_{i_j}) = C_i\, e^{\frac{1}{2}\sum\limits_{l=1}^{k} u_{i_j}\Lambda(u_{i_j})} = C_i\, e^{\frac{\boldsymbol{u}_i \cdot \Lambda(\boldsymbol{u}_i)}{2}}, \quad k = 2 \text{ for double-binary case} \tag{F.8}$$

From the expression derived from Eq. F.6:

$$\gamma(S_{i-1}, S_i) = P(y_i, S_i|S_{i-1})$$

Considering the conditional probability in F.5:

$$\gamma(S_{i-1}, S_i) = \frac{P(y_i, S_i, S_{i-1})}{P(S_{i-1})} = \frac{P(y_i|S_{i-1}, S_i)P(S_{i-1}, S_i)}{P(S_{i-1})} = P(y_i|S_{i-1}, S_i)P(S_i|S_{i-1})$$

One particular observation from the previous equation is the fact that a transition between states depend on the encoder configuration and the input binary sequence. In fact given that the configuration itself is constant it is fairly obvious to see that the $P(S_{i-1}, S_i) = P(u_i)$. On the other hand the occurrence of $S_{i-1} \to S_i$ is directly associated with the output of the convolutional encoder, $x_i$, which means that:

$$\gamma(S_{i-1}, S_i) = P(\mathbf{y}_i|\mathbf{u}_i)P(\mathbf{u}_i) \tag{F.9}$$

Since the communications channel has no memory, each component $y_{il}$ of $\boldsymbol{y}_i$ depends only on the correspondent $\boldsymbol{x}_i$ component $x_{il}$, as such:

$$P(\boldsymbol{y}_i|\boldsymbol{x}_i) = \prod_{l=1}^{n} P(y_{il}|x_{il}) \tag{F.10}$$

Assuming that the sequence $\boldsymbol{x}_i$ will be transmitted using a specific modulation scheme through a AWGN channel, $y_{il} = a \cdot x_{il} + n$, from the Gaussian probability density function, then:

$$P(y_{il}|x_{il}) = \frac{1}{\sqrt{\pi \frac{N_0}{Ec}}} e^{-\frac{E_c}{N_0}(y_{il} - a x_{il})^2}$$

Using the generalized formulation of Eq. F.10 it becomes:

$$P(\boldsymbol{y}_i|\boldsymbol{x}_i) = \frac{1}{\sqrt{\pi \frac{N_0}{Ec}}} e^{-\frac{E_c}{N_0}\sum_{l=1}^{n} y_{il}^2 + a^2 x_{il}^2} e^{2a\frac{E_c}{N_0}\sum_{l=1}^{n} x_{il} y_{il}} = C_2\, e^{2a\frac{E_c}{N_0}\sum_{l=1}^{n} x_{il} y_{il}} \tag{F.11}$$

With Eq. F.8 and F.11 it is possible to rewrite Eq. F.9 as:

$$\gamma(S_{i-1}, S_i) = C_2\, e^{2a\frac{E_c}{N_0}\sum_{l=1}^{n} x_{il} y_{il}} C_1\, e^{\frac{1}{2}\sum_{l=1}^{m} u_{il}\Lambda(u_{il})}$$

With the general formulation of $\gamma$ becoming:

$$\gamma(S_{i-1}, S_i) = C\, e^{\frac{1}{2}\langle \boldsymbol{u}_i, \Lambda(\boldsymbol{u}_i)\rangle + \frac{L_c}{2}\langle \boldsymbol{x}_i, \boldsymbol{y}_i\rangle} \tag{F.12}$$

For the specific case of the decoder used in the IEEE 1901 $n = 3$ in $\gamma$ computation.

The definition of $\alpha(s_{i-1})$ was derived in Eq. F.6 and considering the partitioning of $\boldsymbol{y}$ it can be defined as:

$$\alpha(S_{i-1}) = P(S_{i-1}, y_{<i}) = P(S_{i-1}, y_{<i-1}, y_{i-1})$$

From the law of total probability it can be established that $P(A) = \sum_{i=1}^{n} P(A, B_i) = \sum_{b_i} P(A, B_i)$, where $B_i$ represents a partition of the probability solution space $B$, is valid if $B \subseteq A$. Since $S_{i-2}$ belongs to the same probability space than $S_{i-1}$ it means that the former equation can be rewritten as:

$$\alpha(S_{i-1}) = \sum_{S_{i-2}} P(S_{i-1}, S_{i-2}, y_{<i-1}, y_{i-1}) = \sum_{S_{i-2}} P(S_{i-1}, y_{i-1}|S_{i-2}, y_{<i-1}) P(S_{i-2}, y_{<i-1})$$

Due to memoryless nature of the communications channel:

$$\alpha(S_{i-1}) = \sum_{S_{i-2}} \underbrace{P(S_{i-1}, y_{i-1}|S_{i-2})}_{\gamma(S_{i-2}, S_{i-1})} \underbrace{P(S_{i-2}, y_{<i-1})}_{\alpha(S_{i-2})}$$

From the previous definitions of $\gamma$ and $\alpha$ the following recursive formulation can be established:

$$\alpha(S_{i-1}) = \sum_{S_{i-2}} \gamma(S_{i-2}, S_{i-1})\alpha(S_{i-2}) \implies \alpha(S_i) = \sum_{S_{i-1}} \gamma(S_{i-1}, S_i)\alpha(S_{i-1})$$

Like in the previous case, $\beta(S_i)$ was also defined in Eq. F.6 as:

$$\beta(S_i) = P(y_{>i}|S_i)$$

From the conditional probability definition:

$$\beta(S_i) = \frac{P(y_{>i}, S_i)}{P(S_i)}$$

Applying here the law of total probability as explained previously:

$$\beta(S_i) = \sum_{S_{i+1}} \frac{P(y_{>i}, S_i, S_{i+1})}{P(S_i)}$$

From the partitioning of $\boldsymbol{y}$ and the conditional probability definition in Eq. F.5:

$$\begin{aligned}\beta(S_i) &= \sum_{S_{i+1}} \frac{P(y_{>i+1}, y_{i+1}, S_i, S_{i+1})}{P(S_i)} = \sum_{S_{i+1}} \frac{P(y_{>i+1}|y_{i+1}, S_i, S_{i+1})P(y_{i+1}, S_i, S_{i+1})}{P(S_i)} \\ &= \sum_{S_{i+1}} P(y_{>i+1}|y_{i+1}, S_i, S_{i+1})P(y_{i+1}, S_{i+1}|S_i) = \sum_{S_{i+1}} \underbrace{P(y_{>i+1}|S_{i+1})}_{\beta(S_i)} \underbrace{P(y_{i+1}, S_{i+1}|S_i)}_{\gamma(S_i, S_{i+1})}\end{aligned}$$

From the previous definitions of $\gamma$ and $\beta$ the following recursive formulation can be established:

$$\beta(S_i) = \sum_{S_{i+1}} \beta(S_{i+1})\gamma(S_i, S_{i+1}) \implies \beta(S_{i-1}) = \sum_{S_i} \beta(S_i)\gamma(S_{i-1}, S_i)$$

As shown, the calculation of $\alpha$ and $\beta$ involves the recursive computation using for each iteration the branch metrics and the previous value of respectively $\alpha$ and $\beta$. This is valid for the all n-binary decoding processes, including of course the well-known $n = 2$, the binary decoding, because the nature of the encoding/decoding process is embedded in branch metric $\gamma$.

One particular aspect that still needs to be mentioned is the initial values of both $\alpha$ and $\beta$, $\alpha(S_0)$ and $\beta(S_N)$ respectively. As referred to in Chapter 4 this depends on the closing mechanism used in the encoding process, being that in the one defined by IEEE1901 a circular state is used, which can be estimated with a prologue phase or by assuming that the initial states correspond to zero and using a feedback mechanism of $\alpha$ and $\beta$ metrics, as illustrated in Fig. 4.14.

The BCJR algorithm or forward-backward formulation used in the calculation of intermediate metric can be summarized into:

$$\begin{cases} \alpha(S_i) = \sum\limits_{S_{i-1}} \alpha(S_{i-1})\gamma(S_{i-1}, S_i) \\ \gamma(S_{i-1}, S_i) = C\, e^{\frac{1}{2}\langle \boldsymbol{u}_i, \Lambda(\boldsymbol{u}_i)\rangle + \frac{L_c}{2}\langle \boldsymbol{x}_i, \boldsymbol{y}_i\rangle} \\ \beta(S_{i-1}) = \sum\limits_{S_i} \beta(S_i)\gamma(S_{i-1}, S_i) \end{cases} \tag{F.13}$$

Variants of BCJR are used to allow the implementation of decoding algorithms will less stringent computation requirements and allow simpler HW to be used. There are several algorithms available in the literature but only the classic log-M$a$P and max-log-M$a$P variants were considered. The simplification rationale behind their conception is related with the use of log variants of the intermediate metrics and the difference among them is associated with the implementation of function $f(a,b)$ used in Eq. F.14.

$$\begin{cases} A(S_i) = \log\alpha(S_i) = f\left[(\alpha(S_{i-1})\gamma(S_{i-1},S_i)\right] \\ \Gamma(S_{i-1},S_i) = \log\gamma(S_{i-1},S_i) = \log C + \langle \boldsymbol{u}_i, \Lambda(\boldsymbol{u}_i)\rangle + L_c\langle \boldsymbol{x}_i, \boldsymbol{y}_i\rangle \\ B(S_{i-1}) = \log\beta(S_{i-1}) = f\left[\beta(S_i)\gamma(S_{i-1},S_i)\right] \end{cases} \tag{F.14}$$

The implementations of $f(a,b)$ are summarized in Eq.F.15. On a side note it should be pointed out that $f(a,b,c)$ is typically implemented using the recursive form: $f(a,b,c) = f\left[a, f(b,c)\right]$.

$$f(a,b) = \begin{cases} \max(a,b) + \log(1+e^{-|a-b|}) & \text{(log-M}a\text{P)} \\ \max(a,b) & \text{(max-log-M}a\text{P)} \end{cases} \tag{F.15}$$

Other sub-optimal M$a$P implementations can also be applied, namely constant-log-M$a$P and linear-log-M$a$P variants as pointed out in [138].

One aspect that was not mentioned before has to do with the normalization of the metrics that is implemented to reduce the numeric instability of the computations performed within iterative decoding algorithms. Hence both $\alpha$ and $\beta$ are normalized, which allows also the normalization of the sum of products of $\alpha\cdot\gamma\cdot\beta$ of the numerator and denominator of Eq. F.7. Normalization is critical in the considered turbo decoding architecture, due to the feedback nature of $\alpha$ and $\beta$, as illustrated in Fig. 4.14. As expected the normalization factor does not affect the computation of $\Lambda(\boldsymbol{u}_i|\boldsymbol{y}_i)$ since it represents a ratio.

In the beginning of this Appendix it was emphasized the importance of determining the extrinsic information, which allows the iterative decoding process to take place. As previously stated in Eq. F.1 there is a dependence between the *a posteriori* LLR and the extrinsic information which can also be established for the non-binary case.

From Eq. F.12 it is possible to separate the information from the parity:

$$\gamma(S_{i-1},S_i) = C\, e^{\left(\frac{1}{2}\langle \boldsymbol{u}_i,\Lambda(\boldsymbol{u}_i)\rangle + \frac{L_c}{2}\langle \boldsymbol{x}_i,\boldsymbol{y}_i\rangle\right)} = C\, e^{\left(\frac{1}{2}\boldsymbol{u}_i\cdot\Lambda(\boldsymbol{u}_i)\right)} e^{\frac{L_c}{2}\left(\sum\limits_{j=1}^{k} \boldsymbol{x}_{i_j},\boldsymbol{y}_{i_j}\right)} e^{\frac{L_c}{2}\left(\sum\limits_{j=k+1}^{n} \boldsymbol{x}_{i_j},\boldsymbol{y}_{i_j}\right)}$$

Remembering that $\boldsymbol{x}_i$ without the parity bits is in fact $\boldsymbol{u}_i$ and that $\boldsymbol{y}_i = [\boldsymbol{y}_{i_I}\boldsymbol{y}_{i_p}]$ can be defined through its information and parity components:

$$\gamma(S_{i-1},S_i) = C\, e^{\frac{1}{2}(\boldsymbol{u}_i\cdot\Lambda(\boldsymbol{u}_i) - \boldsymbol{u}_i\cdot\boldsymbol{y}_{i_I})} \underbrace{e^{\frac{L_c}{2}\left(\sum\limits_{j=k+1}^{n} x_{i_J}, y_{i_j}\right)}}_{extrinsic}$$

Replacing $\gamma(S_{i-1}, S_i)$ in Eq. F.7:

$$\Lambda_j(\boldsymbol{u}_i|\boldsymbol{y}_i) = \log \frac{\sum\limits_{\boldsymbol{u}_i=(a,b)} \alpha(S_{i-1}) e^{\frac{1}{2}(\boldsymbol{u}_i \cdot \Lambda(\boldsymbol{u}_i) - \boldsymbol{u}_i \cdot \boldsymbol{y}_{i_l})} e^{\frac{L_c}{2}(\sum\limits_{j=k+1}^{n} x_{i_J}, y_{i_j})} \beta(S_i)}{\sum\limits_{\boldsymbol{u}_i=(\text{-}1,\text{-}1)} \alpha(S_{i-1}) e^{\frac{1}{2}(\boldsymbol{u}_i \cdot \Lambda(\boldsymbol{u}_i) - \boldsymbol{u}_i \cdot \boldsymbol{y}_{i_l})} e^{\frac{L_c}{2}(\sum\limits_{j=k+1}^{n} x_{i_J}, y_{i_j})} \beta(S_i)}$$

$$= \Lambda_j(\boldsymbol{u}_i) + L_c \boldsymbol{y}' + \underbrace{\log \frac{\sum\limits_{\boldsymbol{u}_i=(a,b)} \alpha(S_{i-1}) e^{\frac{L_c}{2}(\sum\limits_{j=k+1}^{n} x_{i_J}, y_{i_j})} \beta(s_i)}{\sum\limits_{\boldsymbol{u}_i=(\text{-}1,\text{-}1)} \alpha(S_{i-1}) e^{\frac{L_c}{2}(\sum\limits_{j=k+1}^{n} x_{i_J}, y_{i_j})} \beta(S_i)}}_{\Lambda_e(\boldsymbol{u}_i)}$$

Therefore, the extrinsic information exchanged between the serial decoders is defined as:

$$\Lambda_{e_j}(\boldsymbol{u}_i) = \Lambda_j(\boldsymbol{u}_i|\boldsymbol{y}_i) - \Lambda_j(\boldsymbol{u}_i) - L_c \boldsymbol{y}'_i \tag{F.16}$$

When comparing the formulation presented in Eq. F.1 for the binary case and Eq. F.16 for the double-binary the main difference, apart from the binary and symbol representation of variables, is found on $\boldsymbol{y}'_i$ components. The formulation of $\boldsymbol{y}'_i$ follows the same rationale used in $\Lambda(\boldsymbol{u}_i)$ where the ratio with the dibit (-1,-1) favors the simplification of $\boldsymbol{y}_i$. Hence, for the double-binary case:

$$\boldsymbol{y}'_i = \begin{cases} y_{i_2}, & u_i = (\text{-}1,1) \\ y_{i_1}, & u_i = (1,\text{-}1) \\ y_{i_2} + y_{i_1}, & u_i = (1,1) \end{cases} \tag{F.17}$$